Canadian Institute of
Guided Ground Transport
Queen's University
at Kingston, Ontario

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CIGGT Report No. 87-8
Transport Canada Report No. TP-9179E

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CIGGT Project No. PRO-733-3

CIGGT Report No. 87-8
Transport Canada Report No. TP-9179E

TRACK SYSTEM MODEL

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Canadian Institute of Guided Ground Transport
Queen's University at Kingston, Ontario
K7L 3N6

March 1988

416498

89-05266/

ISBN 0 88911 061 1

Un sommaire en français de ce rapport est inclus avant la Table des matières.

This report resulted from research conducted through the Canadian Institute of Guided Ground Transport. The report represents the views of the authors and does not necessarily have the endorsement of the University or the other participating organizations.

Transport Canada / Transports Canada

Development / Developpement

REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No.	3. Recipient's Catalogue No.
TP 9179E	6992 (Task 3)	

4. Title and Subtitle	5. Report Date
TRACK SYSTEM MODEL	March 1988
	6. Performing Organization Report No.
7. Author(s)	8. Transport Canada File No.
S.T. Lamson, G.D. Thompson, A.B. Hazell	D1465-6-8
9. Performing Organization Name and Address Canadian Institute of Guided Ground Transport (CIGGT) Queen's University Kingston, Ontario K7L 3N6	10. DSS File No. 14SD.T8200-7-7537
	11. DSS or Transport Canada Contract No. T8200-7-7537/01-SD
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 200 René-Lévesque Blvd. West Suite 601, West Tower Montreal, Quebec H2Z 1X4	13. Type of Report and Period Covered
	14. Sponsoring Agency Code
15. Supplementary Notes	16. TDC Project Officer W.G. Rowan

17. Abstract

A computer model to predict the deterioration of the elements of a track structure is presented. A general overview of the calibration of the model is discussed, and detailed sensitivity analyses have been performed on various input parameters.

18. Key Words	19. Distribution Statement
Track, Rail, Tie, Ballast, Mathematical modelling, Deterioration, Degradation	Available on request from Canadian Institute of Guided Ground Transport and the Transportation Development Centre.

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
Unclassified	Unclassified	21 + append.	---

TDC CDT 79-005
Rev 86

Canada

Transports Canada / Transport Canada

Développement / Development

FORMULE DOCUMENTAIRE DU RAPPORT

1. N° du rapport Transports Canada	2. N° de l'étude — CDT	3. N° de catalogue du destinataire
TP 9179E	6992 (Tâche 3)	

4. Titre et sous-titre	5. Date du rapport
TRACK SYSTEM MODEL	Mars 1988
	6. N° du rapport de l'organisme exécutant

7. Auteur(s)	8. N° de dossier Transports Canada
S.T. Lamson, G.D. Thompson, A.B. Hazell	D1465-6-8

9. Nom et adresse de l'organisme exécutant	10. N° de dossier — ASC
Canadian Institute of Guided Ground Transport (CIGGT) Queen's University Kingston (Ontario) K7L 3N6	14SD.T8200-7-7537
	11. N° de contrat — ASC ou Transports Canada T8200-7-7537/01-SD

12. Nom et adresse de l'organisme parrain	13. Genre de rapport et période visée
Centre de développement des transports (CDT) 200 ouest, boul. René-Lévesque Suite 601, tour ouest Montréal (Québec) H2Z 1X4	14. Code de l'organisme parrain

15. Remarques additionnelles	16. Agent de projet — CDT
	W.G. Rowan

17. Résumé

Présentation d'un modèle informatique permettant de simuler le processus de dégradation d'une voie ferrée, avec la description du processus de calage de ses modules et l'analyse de sa sensibilité à divers indicateurs de la dégradation.

18. Mots-clés	19. Diffusion
Voie, rails, traverses, ballast, modélisation mathématique, dégradation, avaries.	S'adresser au "Canadian Institute of Guided Ground Transport" et au Centre de développement des transports.

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22. Nombre de pages	23. Prix
non classifié	non classifiée	21 + append.	---

Canada

SUMMARY

The introduction of heavier loads and higher speeds on existing Canadian rail infrastructure is likely to incur accelerated degradation of track components (rail, ties and track geometry) at a time when track is becoming less accessible for maintenance. Partial information is now available on the degradation history and current status of track, and it was felt that a computer model linking traffic history to degradation would prove a valuable tool for use by local track maintenance personnel and head office management in improving productivity. To this end, the Track System Model (TSM) was developed using Lotus 1-2-3.

TSM consists of four modules:

- Dynamic Wheel Force Model
- Rail Life Model
- Tie Life Model
- Surface Life Model.

The three models predicting rail life, tie life and required lift and surfacing cycle have been calibrated using data supplied by CN and CP. Parameters tested were:

- annual tonnage
- rail grinding cycle (for Rail Life Model only)
- track geometry
- Ballast Abrasion Index (for Surface Life Model only)
- track modulus
- Tie Age Index (for Tie Life Model only)

A brief outline of each TSM module is given below.

Dynamic Wheel Force Model

The difference between one traffic category and another, in terms of track degradation, begins with the various characteristics of their dynamic wheel loads. Therefore, an estimate of the dynamic wheel load for each traffic category is necessary in order to work out the contribution to total track maintenance costs of different traffic types in a traffic mix. This model gives the required wheel loads.

For each traffic type, there are two principal load components, namely vertical and lateral, each with two principal terms: steady-state and dynamic variation. The steady-state term represents the reaction of the vehicle to the average track parameters such as nominal alignment. The dynamic term represents the reaction of the vehicle to the instantaneous changes in track parameters, such as alignment errors.

The loads obtained from this model are then transferred to the following models, where they are used in determining their effect on the life of the particular track component.

Rail Life Model

Rail damage and associated costs are basically caused by an accumulation of various wheel-loading cycles, each with a different force, depending on vehicle characteristics, operating conditions, and track quality. The wheel loads, as obtained from the Wheel Force Model, are separated into high and low rail forces, and also into flange and tread forces, each causing a particular type of damage. The forces can be normalized so that each equivalent load cycle causes equal amounts of damage, thus establishing the unit of rail cost per cycle.

The key to this approach is to accurately estimate the dynamic force exerted on the rail by each traffic category, and the relative extent of damage the rail sustains when subjected to a cycle of such force.

Tie Life Model

The strategy in this program is that a distinct series of track conditions can be identified and grouped into a finite number of classes. Each track class is considered to represent a unique set of track characteristics, as related to tie damage. The total traffic is also broken into a distinct, finite set of traffic classes, each one representing a unique set of traffic characteristics as related to tie damage.

The analysis is then carried out by considering the net effect on each track class when subjected to loading by each traffic class. A final summation of tie damage allows the total effect per route to be determined.

Surface Life Model

The analysis is carried out on a per-track-class, per-traffic-class basis, until a number of normalized wheel load cycles are generated. The normalization standardizes all traffic-loading cycles according to their relative significance to track surface degradation. After the total number of normalized wheel load cycles is calculated for a track class, the surfacing cycle and required lift are estimated.

The work reported herein, conducted under contract with the Transportation Development Centre, was limited to the development of a method of calibrating the model and carrying out a sensitivity analysis on the input variables of the CIGGT model to determine their effect on track degradation.

The following conclusions may be drawn from the sensitivity runs on the TSM:

Rail Life:

1. The model is most affected by changes in the degree of curvature and the rail grinding cycle.

2. Only a small change in rail life occurs when the speed is varied.

3. As the input variables are increased, the rail life decreases.

Tie Life:

1. The effect of increasing tonnage increases with the degree of curvature.

2. An increase in the input parameters causes an increase in the number of ties needing replacement each year.

3. The number of ties needing annual replacement is most affected by an increase in tonnage.

Surface Life:

1. Degree of curvature has a limited effect on the surfacing cycle.

2. The track geometry rating has the greatest effect on the surfacing cycle.

3. An increase in the input variables (with the exception of track modulus) causes a decrease in the surfacing cycle.

SOMMAIRE

L'alourdissement des trafics circulant sur les voies ferrées du Canada et le relèvement des vitesses pratiquées font que le processus de dégradation des éléments de voie (rails et traverses) ainsi que de leur géométrie risquent de s'accélérer, alors même que le réseau ferroviaire est de plus en plus occupé, donc de moins en moins disponible à l'entretien. On dispose actuellement d'informations partielles sur le processus de dégradation et sur l'état des voies; aussi a-t-il été estimé utile de disposer d'un modèle informatique pouvant faire le lien entre défauts de voie et caractéristiques du trafic écoulé et constituant un outil de décision précieux tant pour le personnel d'entretien que pour la haute direction désireuse de relever la productivité de ses opérations. Le Track System Model sur le logiciel Lotus 1-2-3 a donc été élaboré dans cette optique.

Ce modèle comporte les quatre modules suivants:

- module "efforts dynamiques roue-rail",
- module rails,
- module traverses,
- module géométrie de voie.

Le calage des modules rails, traverses et géométrie de voie (opérations de soufflage et de nivellement-dressage) a été fait à partir des données fournies par le CN et le CP, les principaux indicateurs pris en compte étant les suivants:

- tonnage transporté annuellement,
- périodicité du meulage (module rails seulement),
- géométrie de voie,
- indice d'abrasion du ballast (module géométrie de voie seulement),
- module de voie,
- indice de vieillissement (module traverses seulement).

Voici une description de ces quatre modules.

Module dynamique

Pour bien caractériser les différents types de trafics en fonction des dégradations qu'ils provoquent, il faut commencer par bien déterminer les charges dynamiques qui les caractérisent. Il faut donc connaître approximativement les charges dynamiques correspondant à chaque type de trafic avant de pouvoir établir la quote-part de ceux-ci dans le coût total de maintenance. Ce module fournit les données nécessaires à cet égard.

Tout trafic se décompose en deux composantes principales de charge: charges verticales et charges transversales, celles-ci à leur tour se définissant par le régime qui peut être soit permanent, soit transitoire. Par régime permanent, on entend la composante correspondant aux valeurs moyennes des indicateurs clés, le nivellement nominal, par exemple. Par régime transitoire, on entend la composante correspondant aux valeurs instantanées de ces indicateurs, les défauts d'alignement, par exemple.

Les valeurs de charge tirées de ce module sont alors transférées aux modules suivants qui s'en servent pour calculer leur effet sur l'élément de voie traité.

Module rails

Les avaries de rails et les coûts y relatifs sont induits par la conjonction de trafics, donc de cycles de charge très variables en nature, vitesse et intensité. Les valeurs de charge tirées du module dynamique sont décomposées en forces exercées sur les rails extérieurs, d'une part, et intérieurs, d'autre part, mais aussi en forces transversales et verticales, chacune de ces forces induisant des avaries d'un type particulier. Ces forces peuvent être normalisées de façon que les cycles de charge équivalents induisent des effets égaux, dont il sera possible par la suite de tirer des coûts unitaires par cycle.

L'essentiel de cette approche est d'estimer avec précision, d'une part, les charges dynamiques par type de trafic et, d'autre part, la sévérité correspondante des avaries.

Module traverses

La stratégie qui sous-tend ce module consiste à identifier des séries de conditions géométriques de voie et à les grouper à l'intérieur d'un nombre fini de classes distinctes, chacune représentant un ensemble particulier de caractéristiques géométriques rapportées aux défauts induits dans les traverses.

Quant au trafic total, il est lui aussi subdivisé en un nombre fini de types de trafics distincts, chacun représentant un ensemble particulier de caractéristiques de trafic rapportées aux défauts induits dans les traverses.

L'analyse consiste alors à identifier l'effet net de chacun des types de trafic sur chacune des classes de voies pour en tirer par sommation l'effet total induit dans les traverses par l'ensemble du trafic sur la ligne considérée.

Module géométrie de voie

L'analyse consiste, ici aussi, à identifier l'effet des différents trafics sur les différentes classes de voies, aboutissant à un certain nombre de cycles de charge normalisés qui définissent la relation entre trafic et charge, d'une part, et dégradation de voie, d'autre part. Lorsque le nombre total des cycles de charge normalisés a été déterminé à l'égard d'une voie donnée, on établit la périodicité des opérations de nivellement-dressage et l'amplitude des opérations de soufflage.

La recherche dont il est rendu compte ici, commanditée par le Centre de développement des transports, s'est limitée à la mise au point d'une méthode de calage du modèle et à l'analyse de la sensibilité du modèle à divers indicateurs de la dégradation.

Cette analyse a donné lieu aux constatations suivantes:

Rails

1. Une très grande sensibilité aux variations du rayon de courbure et de la périodicité du meulage.
2. Une très faible sensibilité au paramètre vitesse.
3. La durée de vie du rail diminue lorsque la valeur des variables explicatives augmente.

Traverses

1. L'effet d'un accroissement du tonnage augmente avec le rayon de courbure.
2. Plus la valeur des paramètres d'entrée augmente, plus grand est le nombre de traverses devant être changées chaque année.
3. L'accroissement du tonnage a un effet radical sur le nombre de traverses devant être remplacées chaque année.

Géométrie de voie

1. La périodicité des opérations de nivellement-dressage a peu à voir avec le rayon de courbure.
2. Cette périodicité est directement reliée à la cotation donnée à la voie.
3. La périodicité des opérations de nivellement-dressage diminue lorsque la valeur des variables explicatives augmente (module de voie excepté).

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1. INTRODUCTION

In recent years, the transportation industry has become increasingly competitive, with traffic volumes growing substantially. This type of market has resulted in increasing pressure being put on the Canadian rail industry to allow heavier loads on the track structure at higher speeds. If this type of traffic is allowed onto the track structure, the degradation of all track components -- rail, ties and track geometry -- is likely to occur at increased rates, when less time is available on the track for maintenance purposes.

For a relatively long time, the railways have maintained an extensive computerized data base on track performance. Partial information is now available on the degradation history and current status of track components and geometry. A computer model linking traffic history to track degradation would allow the railways to make better use of available information. This tool can also be used by track maintenance personnel at local sites, as well as by head office management, to improve overall productivity.

Work on the Track System Model (TSM) began in 1983, as a long-term program aimed at developing practical and cost-effective techniques to reduce track geometry and component deterioration, and at developing a systematic approach to maintenance planning to improve cost and time efficiency.

Since that time, a relationship has been formulated between traffic loading and track response based on current knowledge of vehicle dynamics and track behaviour. Also developed is a program to convert track geometry error data into computer files for vehicle/track dynamic interaction analysis. The programs enable the characterization of any sample track section and the conversion of the track geometry data into the right format for vehicle dynamic simulation studies.

A set of computer programs has also been developed to simulate the dynamic response of a vehicle over a sample of actual track. These models permit the estimation of vertical and lateral wheel forces produced by a given vehicle running at a given speed over a track with a certain geometry error. The results from this model are then fed into three deterioration models as input.

To facilitate calibration of TSM, CIGGT used values supplied by CP Rail on their Cascade and Thompson Subdivisions and by CN Rail on the Kingston Subdivision.

2. OBJECTIVE

The work reported herein had as its main objectives:

- development of a method of calibration for the Track System Model;
- identification of the most important input variables with respect to track degradation;
- performance of a sensitivity analysis on the variables to determine their effect on track degradation.

This work was sponsored by the Transportation Development Centre (TDC) of Transport Canada.

3. USING THE TRACK SYSTEM MODEL

Set out below are step-by-step instructions for using the Track System Model.

The file TSM.WK1 is a skeleton file which must be expanded to suit the needs of each modelling situation. Before using TSM, the user should gather all traffic and track information for the rail system. The model description will provide a detailed list of the required inputs.

Once the input data has been gathered, run 1-2-3, using the File Retrieve (/FR) command to load the TSM worksheet. The model will immediately ask for the total number of traffic classes to be use. Enter the number and hit [RETURN]. TSM will add the required number of rows to accommodate the request. Enter the traffic-dependent parameters for tangent track.

(Note that TSM requires at least two traffic classes. The case of a single type of traffic can be accommodated by entering the same traffic parameters for both rows and simply splitting the total tonnage for that traffic class between the two rows.)

After the traffic information has been entered, hit [Alt-M] to bring up the TSM commands menu and select the "Expand" option to add one or more track classes. For each new track class, TSM will duplicate the information contained in the first track class. Replace that information with the appropriate parameters collected for the types of track.

A new track class may be added at any time using the above procedure. If an additional traffic category is to be introduced:

- insert a row into the **middle** of each track class where that traffic will be found;
- copy [/C] the **entire** row above the inserted (blank) row into the new row;.
- replace the traffic-dependent parameters with the values for the new traffic class.

(There is no automated procedure for adding a traffic class.)

When using the model, remember that the Surface Life Model must be re-calculated using the macro ([Alt-M] and [RETURN]). The Rail Life and Tie Life results are updated each time the worksheet is recalculated.

4. GENERAL OVERVIEW

The present LOTUS version of the TSM is made up of four separate submodels:

(1) Dynamic Force Model
(2) Tie Life Model
(3) Surface Life Model
(4) Rail Life Model

Figure 1 is a block diagram showing the relationship between each portion of the TSM.

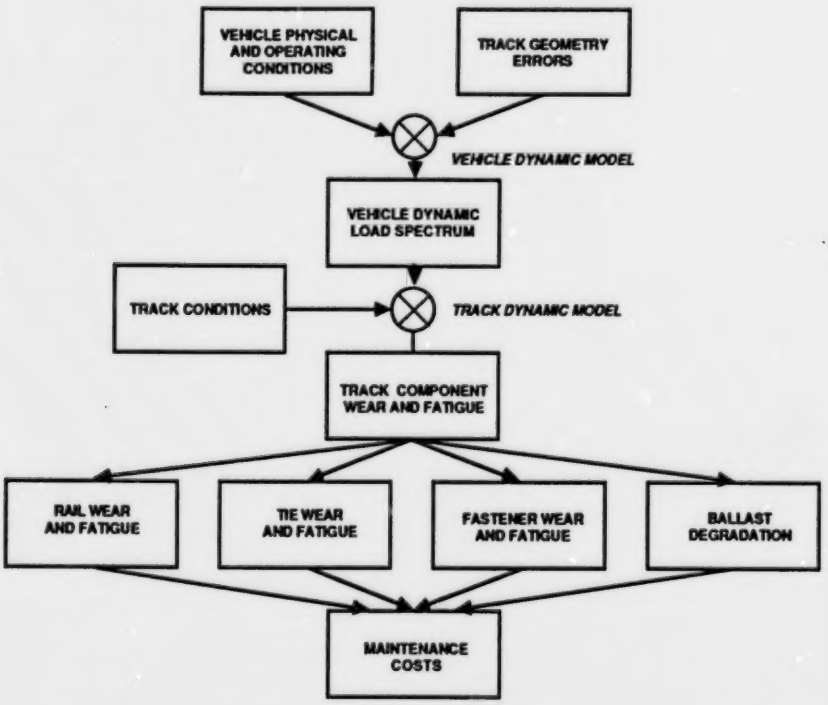

Figure 1 Track System Model

Figure 2 shows the flowchart representing the operation of the Force Model. This model produces key components of the dynamic wheel load for each set of track and traffic data. The outputs from this model are then fed into the other three models as input, and the degradation of the appropriate elements of the track system are then calculated. The Force Model will not be discussed in detail in this report. If the reader is interested in further information on this topic, he is encouraged to contact the Information Officer at CIGGT, and request report number 86-35[1].

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[1] *State-of-the-Art Track Technology and Its Application to Improve Track Component Performance and Track Maintenance Management*, A. Moucessian, S.T. Lamson, J.C. Michaud, C.J. Boon, CIGGT Report NO. 86-35, April 1987.

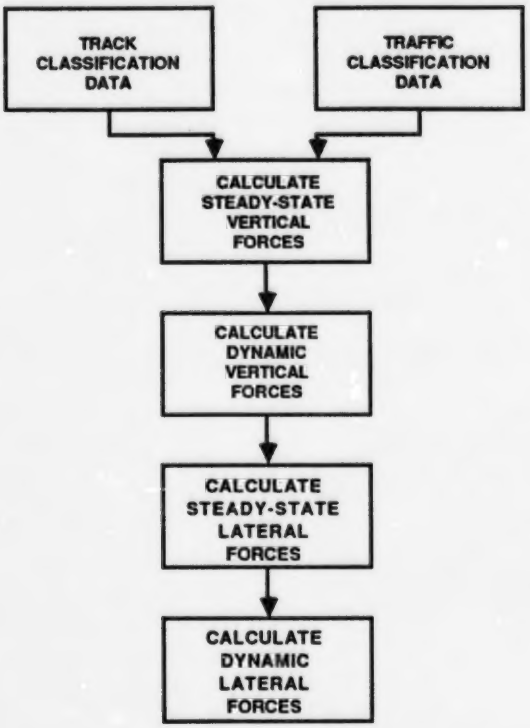


Figure 2 Force Model

The TSM operates on the basis of a normalized wheel load, determining the effects of different types of traffic on different have track in terms of a standardized traffic category. In the TSM, this traffic category is the 100-ton car.

4.1 Tie Life Model

Figure 3 is the flowchart representing the basic steps in the Tie Life Model. If the nominal axle load, annual tonnage and track condition are known, the Dynamic Forces Model can calculate the vertical and lateral forces affecting the ties, which results in certain associated tie stresses. The Tie Life Model uses these stresses to calculate the appropriate tie degradation due to cutting, splitting, and decay.

As with any computer simulation model, the success of the Tie Life Model relies heavily on the availability of good data. It was found that CP's Cascade Subdivision provided a good basis to perform preliminary calibration of the model.

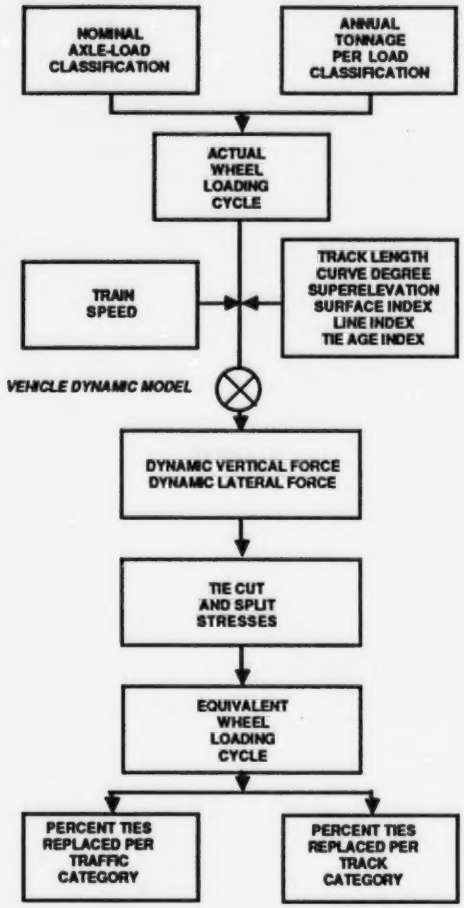


Figure 3 Tie Life Model

The following types of information are required:

- traffic category breakdown: tonnage, axle load, vehicle type, speed;
- track category breakdown: length, geometry, environment, tie type; and
- tie failure breakdown: cutting, splitting, decay, etc.

The inputs required for the computer model are:

- for each traffic category:
  - nominal axle load
  - annual tonnage

- for each track category:
  - average speed
  - track length
  - degree of curvature
  - superelevation
  - surface roughness index
  - alignment roughness index
  - tie age index.

Table 1 lists the approximate traffic and track conditions for the seventeen-year period from 1965 to 1982.

TABLE 1

CP TIE REPLACEMENT DATA -- CASCADE SUBDIVISION*

	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Ties (000)§	33	25.8	31	45	1.2	2.0	32.4	24	20.9	68.6	8.1	15.2	33.6	29.5	11.4	85.9	51.7	59.4
MGT	20.4	22.3	22.9	23.8	23.5	26.9	30.7	33.1	36.8	(36)	35.8	34.3	37.5	41.3	41.4	40.5	45.8	44.7
Percent MGT:																		
% 100-ton¶	0	0	0	2	5	9	14	19	24	29	33	36	39	42	45	47	48.5	50
% empty**	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
% general§§	76	76	76	74	71	67	62	57	52	47	43	40	37	34	31	29	27.5	26
Percent CWR	0	0	0	0	0	3	6	10	16	22	28	35	42.5	50	60	70	79.5	89
Percent BJR	100	100	100	100	100	97	94	90	84	78	72	65	67.5	50	40	30	20.5	11

	Distance (miles)	No. of Spikes	Plate	Speed (mph)	Super-elevation	Deficiency
Tangent	78	2	14"	45	0	0
Up to 3° curve	25	3	14"	40	1"	(-1")
3° to 6° curve	37	5	18"	35	2"	(-1.8")
Greater than 6° curve	25	5	18"	30	2.5"	(-2")

* From R. McIlveen, Financial Planning Department, CP

§ Total: 578,800 ties (total ties in 165 mile section: approx. 500,000)

¶ 33-ton axle load

** 8-ton axle load

§§ 20-ton axle load

The Tie Life Model uses the following parameters for the calibration of the model:

(1) Tie Age Index (k) = 1.5. This value is kept constant for all years, since with the total replacement of 578,800 ties, all ties in this track section have been replaced once, resulting in a constant overall tie age in the population.

(2) Tie loss per MGT = 124. This is a calibration factor, selected to match the total predicted tie loss with the actual total ties replaced. The calibration is based on seventeen years of aggregated data and does not influence the year-to-year fluctuation.

(3) Tie failure mode distribution is estimated as follows:

CP Data

	% Derail-ment	% Broken	% Decay	% Cut	% Split	% Spike Killed
Tangent (78 miles)	0	0	14	22	50	14
Curves (87 miles)	6	2	4	42	42	4
Weighted breakdown for all track	4	1.3	7.3	35.4	44.7	7.3

Aggregated Failure Mode

- mechanical (traffic dependant):

  cut = percent cut + percent broken
  = 35.4 + 1.3 = 36.7%

  split = percent split + percent spike killed + percent derailment
  = 44.7 + 7.3 + 4 = 56%

- other (traffic independent):

  decay = 7.3%

(4) Tie stress equations, based on tie plate and spike data given in Table 1, are as follows:

- plate cutting stress:

  for tangent and shallow curves (3 degrees):
  stress = 0.009V + 0.028F

  for sharper curves (>3):
  stress = 0.007V + 0.017F

- end splitting stress:

  for tangent: stress = 0.06V + 0.228F

  for shallow curves: stress = 0.06V + 0.152F

  for sharper curves: stress = 0.06V + 0.091F

where: V = vertical seat load
F = lateral seat load

Note that there are many outside factors influencing tie replacement, other than deterioration, which would account for some of the scatter of the data points. With this taken into account, Figure 4 shows that the model follows the general trend in actual practice. This model can be used as a reliable tool in the prediction of tie replacement needs.

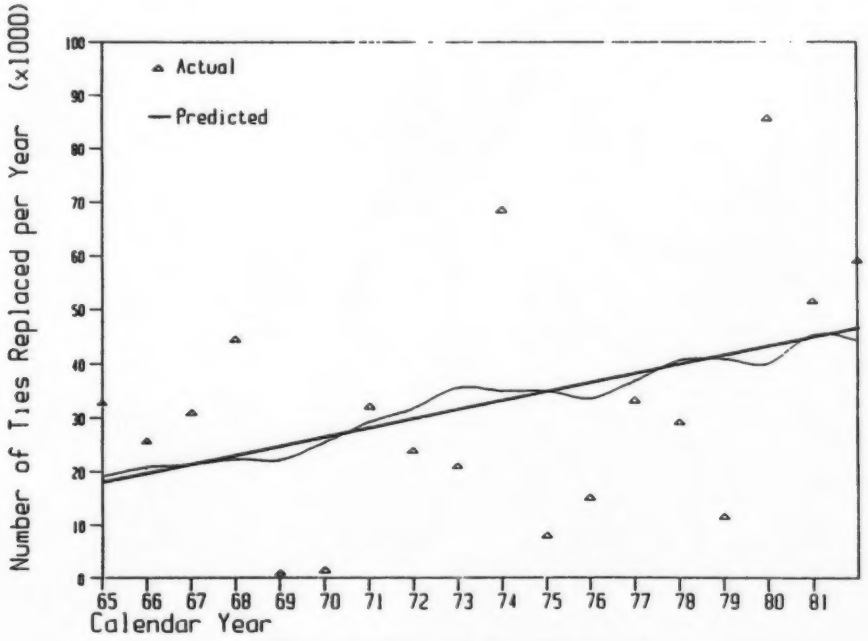


Figure 4 Annual tie replacement

4.2 Surface Model

Figure 5 represents the process by which the track geometry deteriorates under loads. The structure of the model keeps the analysis simple, while allowing the upgrade of individual components.

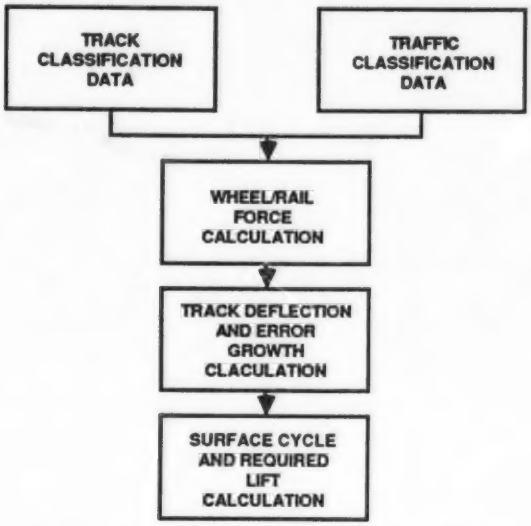

TRACK CLASSIFICATION DATA
TRAFFIC CLASSIFICATION DATA
WHEEL/RAIL FORCE CALCULATION
TRACK DEFLECTION AND ERROR GROWTH CLACULATION
SURFACE CYCLE AND REQUIRED LIFT CALCULATION

Figure 5 Surface Life Model flowchart

The original calibration for this model was done using Kingston Subdivision data from CN. Data from the track geometry car was used, as well as historical track maintenance data.

The basic method for the calibration of this model is as follows:

(1) select the calibration track
(2) establish track error growth
(3) calculate the equivalent loading cycles
(4) calculate the calibration constants.

(1) The calibration track, as mentioned above, is a length of track in the Kingston Subdivision. This portion of track meets the basic requirements for calibration, namely: the traffic mix is known, the maintenance history of the track is known, and there are sufficient track geometry records for the track.

(2) The track error growth characteristics of the track are usually determined from the track geometry car. The track length is divided into sections with a common time from the last tamping. For each section, the mean and standard deviation of the track error is calculated.

(3) The equivalent cycle since the last surfacing cycle is found by accumulating the amount of traffic over the track since the last tamping took place, and

running the dynamic force submodel. The total amount of equivalent cycles is found by summing all the traffic types over each section of track. The result is as follows:

Years Since Surfacing	Number of Equivalent Cycles
0	Neq_0
1	Neq_1
2	Neq_2
Q	Neq_Q

(4) The calibration constants needed for the surface model are:

A,B = relating mean track error to equivalent cycles

C,D = relating standard deviation of track error to equivalent cycles.

These constants are derived from linear regression of the track error versus the equivalent cycles. The results of the equations have the form:

Mean Error: $x = A*Neq + B$
Standard Deviation: $s = C*Neq + D$

The values for the coefficients are found from Figures 6 and 7, with the constants found being used in the Surface Life Model:

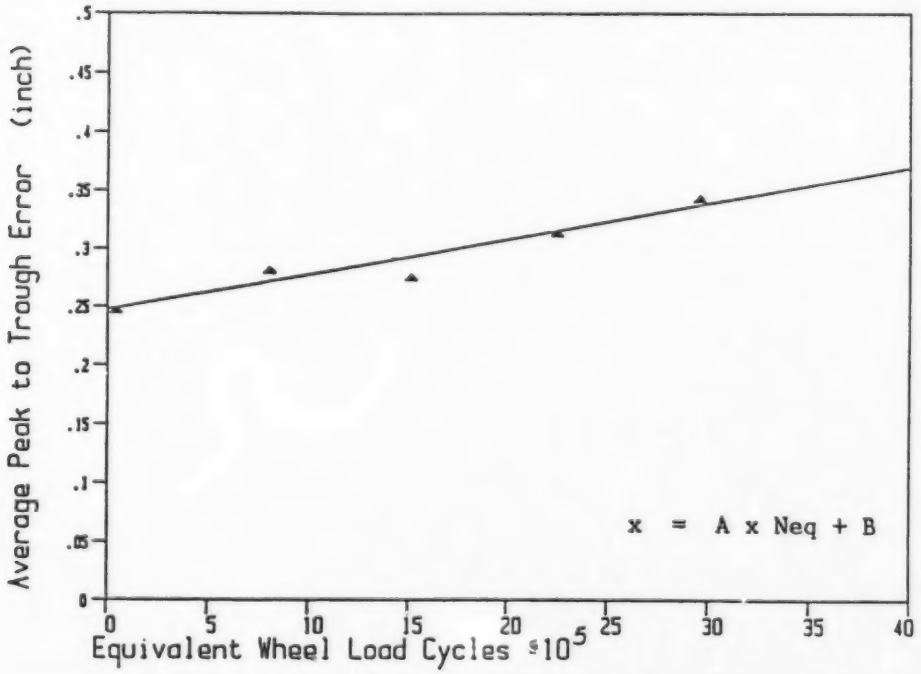


Figure 6 Average peak to trough error

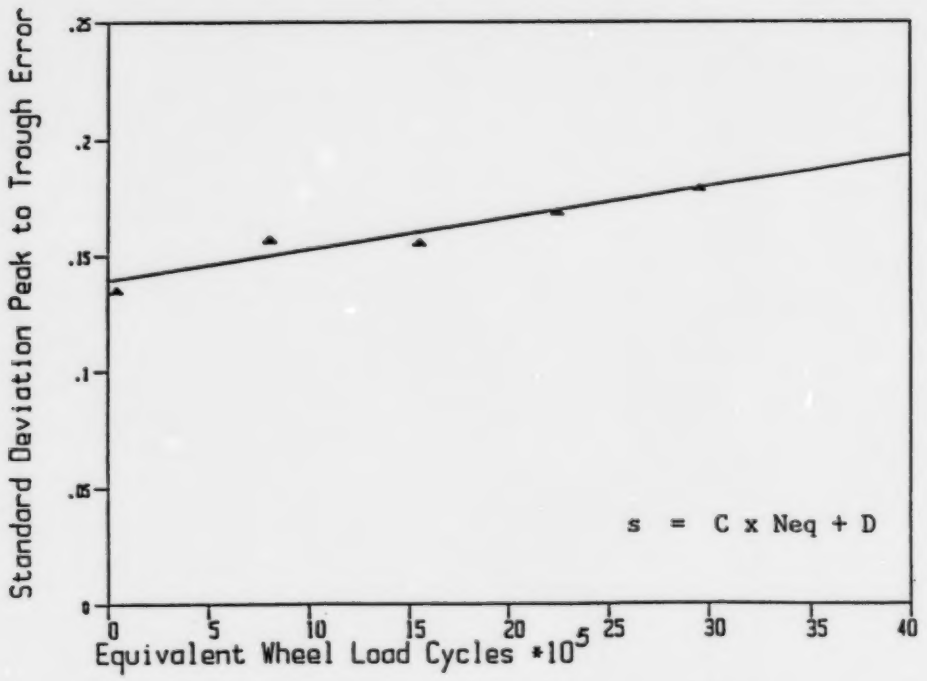


Figure 7 Standard deviation of peak to trough error

The surfacing cycle is then calculated to permit the maximum time or tonnage while keeping the cumulative track error under the specified limit.

The following equation was developed and used in the Surface Life Model to estimate the depth of fouled ballast:

$$D_f = 3.37\ E - 5\ (I_a)^{1.54} \times nX\ (in.)$$

where: n = year
X = annual tonnage (MGT)

The lift, however, should be slightly greater than D_f, therefore:

$$D_l = 1.175 * D_f$$

4.3 Rail Life Model

Figure 8 represents the operation of the Rail Life Model.

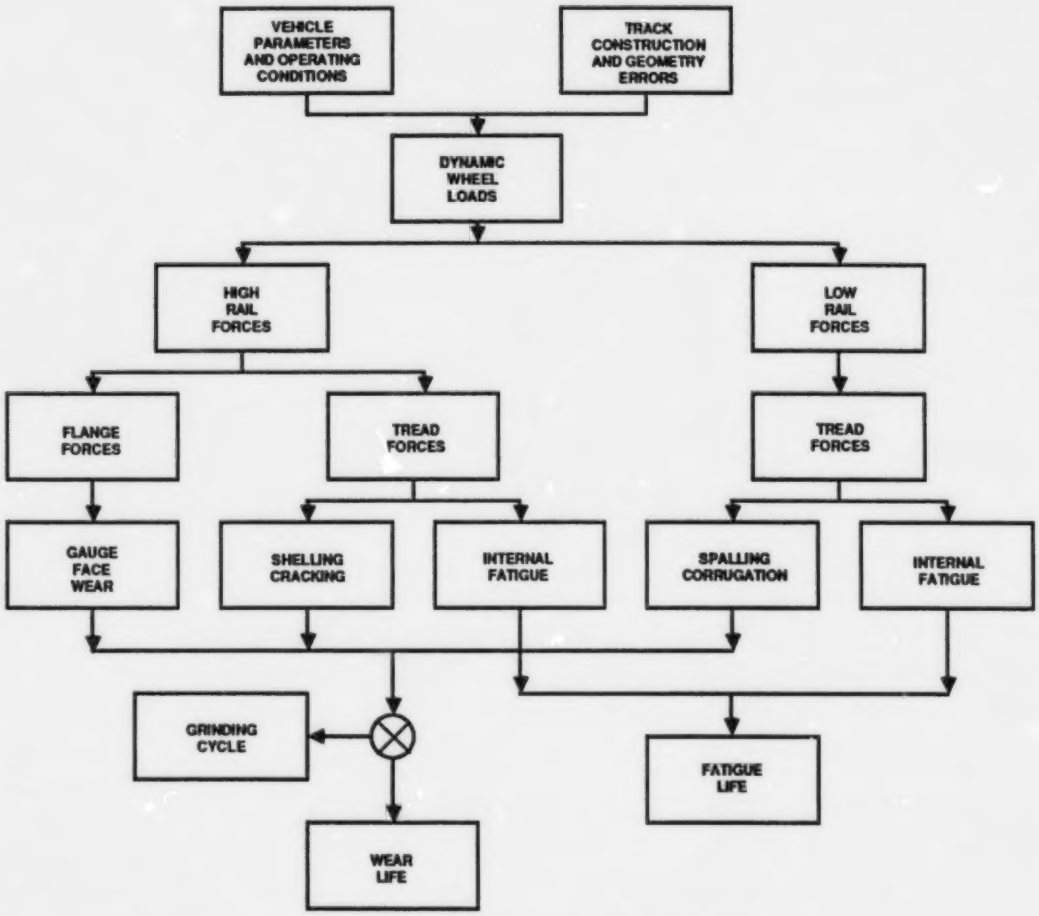


Figure 8 Concept of Rail Life/Cost Model

A preliminary calibration of the Rail Life Model was made using data on rail life gained on CP's Cascade and Thompson Subdivisions. This data was collected during the rail grinding research project carried out between 1981 and 1987. Chrome rail life was adjusted to Standard Carbon-equivalent life by a factor of 1.15.

Two rail lives were calculated: **wear** life is based on head loss due to curving force; **fatigue** life is based on vertical and lateral tread force on the rail head. Tangent track is also subjected to some gauge face wear as there is intermittent flanging due to vehicle lateral dynamics. The tendency to develop this is described by a probability-of-flanging equation as given below:

$$P = 0.95 (1-\exp(-0.39 D) + 0.05$$

where: D = degree of curve

The effect of rail grinding on rail life is modelled on the basis that frequent grinding to remove rail surface fatigue will allow fuller use of the rail head loss limit. Observation of rail life limit on the Québec Cartier Railway where surface fatigue removal (except for corrugation removal) was not routinely done, shows that head loss at the time of replacement was only 8 to 10%. For typical Canadian heavy-haul railways, the current head wear limit is typically about 35%. This limit is reached, however, only if grinding is applied frequently, so that surface fatigue is adequately controlled. Also, since rail life in a curve or tangent track section is determined by the worst location, dynamic wheel impact load is based on three standard deviations.

5. SENSITIVITY RUNS

5.1 General

Once the calibration of the model was considered satisfactory, a sensitivity analysis was done on several parameters to see how their change would affect the overall tie replacement requirements.

The following parameters were chosen as variables:

- annual tonnage
- rail grinding cycle (for Rail Model only)
- track geometry
- Ballast Abrasion Index (for Surface Model only)
- track modulus.
- Tie Age Index (for Tie Model only)

In order to see what effect a change in these parameters would have, a base case of traffic and track conditions were chosen. The base case was with respect to either the Cascade or Kingston Subdivision, depending in which area the calibration was done.

It was decided that runs of the model would be made for parameter values up to 30% above and below the base case. It was felt that this range represented what would normally be considered likely changes to present conditions, and would show any trends in the associated wear of the elements.

5.2 Tie Life Model

The base case for this model is the Cascade Subdivision, with the input values as listed in Table 2.

The graphs in Appendix A are the results of the sensitivity runs. As can be seen, all relationships have a linear correlation. The values plotted are the input variable as a percentage of the base case versus the ties needing replacement produced by that traffic. Graphs A1 through A3 combine all track categories, whereas graphs A4 through A6 separate the tangent track and different degrees of curvature. This was felt to be important, since a sharper curve would be more greatly affected by changes in the input parameters. Although the relationships are linear over each type of track category, it can be seen that the number of ties needing replacement increases with the degree of curvature. Also included as graph A7 are the results of a base case run with the independent variable being curvature, having the results separated with respect to the type of car. This graph clearly illustrates the large effect of running locomotives on the track. For curves 5 degrees and greater, the number of spikes per tie plate and the size of the plate are increased, resulting in a decrease in the associated cut and split stresses, hence a decrease in the number of ties needing replacement annually. This is the reason for the decrease between the 2 and 5 degree curves. If the plate size had remained constant throughout, the resulting effect would have been as in graphs A8 and A9.

TABLE 2

INPUT VALUES, CASCADE SUBDIVISION

Nom. Axle Load (US ton)	Annual Tonnage (US ton)	Average Speed (mph)	Track Length (mile)	Degree of Curve	Super-elevation (in.)	Surface Index	Align-ment Index	Tie Age Index
8.00	10728000.00	45.00	78.00	0.00	0.00	1.02	1.02	1.50
20.00	11622000.00	45.00	78.00	0.00	0.00	1.02	1.02	1.50
33.00	22350000.00	45.00	78.00	0.00	0.00	1.02	1.02	1.50
8.00	10728000.00	40.0	25.0	2.00	1.00	1.02	1.02	1.50
20.00	11622000.00	40.0	25.0	2.00	1.00	1.02	1.02	1.50
33.00	22350000.00	40.0	25.0	2.00	1.00	1.02	1.02	1.50
8.00	10728000.00	35.00	37.00	5.00	2.00	1.07	1.07	1.50
20.00	11622000.00	35.00	37.00	5.00	2.00	1.07	1.07	1.50
33.00	22350000.00	35.00	37.00	5.00	2.00	1.07	1.07	1.50
8.00	10728000.00	30.00	25.00	8.00	2.50	1.07	1.07	1.50
20.00	11622000.00	30.00	25.00	8.00	2.50	1.07	1.07	1.50
33.00	22350000.00	30.00	25.00	8.00	2.50	1.07	1.07	1.50

For this model, the rail seat load, which is a result of the track modulus, was assumed to be a constant, with a value of 0.3. If one wishes to determine the response of ties due to a change in the track modulus, this value must be re-calibrated for each run.

5.3 Surface Life Model

This model was calibrated with actual Kingston Subdivision track geometry data and actual surfacing cycle (three years) (see Table 3).

For this model, the graphs included in Appendix B show the change in the surfacing cycle resulting from changes in the parameters, expressed as a percentage of the base case.

In this model, we found that all five of the inputs had an effect on the surfacing cycle and the lift required. As was expected, as the input variables increased, the surfacing cycle decreased.

There was no significant difference in the surfacing cycle with respect to the degree of curvature, as can be seen in graphs B1 through B5. For this reason, it was not considered necessary to combine the track classes as was done for the Tie Life Model. The variation due to the increase in parameters is much more significant to the resulting surface cycle.

TABLE 3

TRACK GEOMETRY DATA - KINGSTON SUBDIVISION

Track Category	Traffic Category	Nom. Axle Load (US ton)	Unsprung Mass per Axle (lb)	Break-down (US ton)	Avg. Speed (mph)	Track Length (mile)	Curve (degree)
CWR Tangent	100-ton empty	0.00	3142	10728000	60	351.6	0.00
	70-ton general	20.00	2425	1162200	60	351.6	0.00
	passenger	18.00	3142	200000	90	351.6	0.00
	6-axle loco	32.35	8671	300000	60	351.6	0.00
	100-ton loaded	33.00	3142	22340000	60	351.6	0.00
1-2 degrees	100-ton empty	8.0	3142	10728000	60	54.4	0.64
	70-ton general	20.00	2425	11622000	60	54.4	0.64
	passenger	18.00	3142	200000	88	54.4	0.64
	6-axle loco	32.25	8671	300000	60	54.4	0.64
	100-ton loaded	33.00	3142	22350000	60	54.4	0.64
2-4 degrees	100-ton empty	8.00	3142	10728000	59	87.4	1.45
	70-ton general	20.00	2425	11622000	59	87.4	1.45
	passenger	18.00	3142	200000	79	87.4	1.45
	6-axle loco	32.35	8671	300000	59	87.4	1.45
	100-ton loaded	33.00	3142	22350000	59	87.4	1.45

Track Category	Traffic Category	Super-elevation (in.)	Avg. Surface Error (sigma)	Avg. Xlevel Error (sigma)	Avg. Alignment Error (sigma)	Tie Age Index	Tie Spacing (in.)
CWR tangent	100-ton empty	0.00	161	127	49.0	1.5	21
	70-ton general	0.00	161	127	49.0	1.5	21
	passenger	0.00	161	127	49.0	1.5	21
	6-axle loco	0.00	161	127	49.0	1.5	21
	100-ton loaded	0.00	161	127	49.0	1.5	21
1-2 degees	100-ton empty	1.53	165	134	49.0	1.5	21
	70-ton general	1.53	165	134	49.0	1.5	21
	passenger	1.53	165	134	49.0	1.5	21
	6-axle loco	1.53	165	134	49.0	1.5	21
	100-ton loaded	1.53	165	134	49.0	1.5	21
2-4 degrees	100-ton empty	3.36	170	134	49.0	1.5	21
	70-ton general	3.36	170	134	49.0	1.5	21
	passenger	3.36	170	134	49.0	1.5	21
	6-axle loco	3.36	170	134	49.0	1.5	21
	100-ton loaded	3.36	170	134	49.0	1.5	21

Track Category	Traffic Category	Rail EI $_2$ (lb.in^2)	Ballast Grade	Ballast Cond'n Index	Ballast Abrasion Index	Track Modulus (lb/in/in)
CWR tangent	100-ton empty	2.64E+09	4	1	79	3000
	70-ton general	2.64E+09	4	1	79	3000
	passenger	2.64E+09	4	1	79	3000
	6-axle loco	2.64E+09	4	1	79	3000
	100-ton loaded	2.64E+09	4	1	79	3000
1-2 degrees	100-ton empty	2.64E+09	4	1	61	3000
	70-ton general	2.64E+09	4	1	61	3000
	passenger	2.64E+09	4	1	61	2929
	6-axle loco	2.64E+09	4	1	61	2929
	100-ton loaded	2.64E+09	4	1	61	3000
2-4 degrees	100-ton empty	2.64E+09	4	1	61	3000
	70-ton general	2.64E+09	4	1	61	3000
	passenger	2.64E+09	4	1	61	2929
	6-axle loco	2.64E+09	4	1	61	2929
	100-ton loaded	2.64E+09	4	1	61	3000

5.4 Rail Life Model

Appendix C contains graphs illustrating the results from the sensitivity runs on the Rail Life Model.

The base case for this model was the Cascade Subdivision. The output from this model is in both wear life (years) and fatigue life (years). The results from varying the tonnage are separated out into tangent and curved track, to make the relationships a little clearer. For this set of graphs, the grinding cycle was kept constant through the increases.

As can be seen from the graphs in Appendix C, the dominating factor in the life of the rail is the degree of curvature. Speed has a small effect on rail life compared to curvature and rail grinding cycle.

It was found that the Rail Life portion of the Model was not as sensitive to the effect of speed as it should have been. Modifications were made to the program to allow the dynamic vertical load factor and the flange impact factor to increase to a value of 3*SIGMA, as opposed to the SIGMA value used in the Tie and Surface Life Models. These results were found to be more reasonable, and are shown in graph C6.

6. APPLICATION OF TRACK SYSTEM MODEL TO COMPONENT IMPROVEMENT AND MAINTENANCE MANAGEMENT

The Track System Model can be used effectively to improve track component life and optimize track management decisions.

The model must be calibrated to reflect the current nature of the track system and its condition. It must be qualitatively validated to be useful. That is, the trends it produces must match actual system characteristics or at least be agreeable with the experience and/or opinions of track maintenance personnel. There is always a problem with insufficient or distorted data. Therefore, engineering judgments are always necessary. Despite this, the TSM approach is, in the long run, more objective, rational, orderly, and technically superior to any individual track person's opinion. It is a vehicle in which all available knowledge and experience can be incorporated.

To improve track component life, one must first identify the relative contribution to the actual track component replacement by each known deterioration mechanism. For example, rail life is known to be affected by corrugation, shelling, gauge face wear and surface fatigue defects. However, the extent of the contribution to actual rail replacement made varies from case to case. In places where surface fatigue defects are the main cause of premature rail changeout, measures which are effective against this problem can be identified and evaluated using TSM to guide an implementation decision.

TSM can also be used to optimize the frequency and extent of existing maintenance routines to maximize their benefit in terms of component life and/or maintenance costs. One well-known example of this is the optimization of rail grinding cycles. The experience of the Australian iron ore railways has shown that an optimal grinding cycle can be developed to both increase rail life and reduce grinding costs.

7. CONCLUSIONS

The following conclusions may be drawn from the sensitivity runs on the TSM:

Rail Life:

1. The model is most affected by changes in the degree of curvature and the rail grinding cycle.

2. Only a small change in rail life occurs when the speed is varied.

3. As the input variables are increased, the rail life decreases.

Tie Life:

1. The effect of increasing tonnage increases with the degree of curvature.

2. An increase in the input parameters causes an increase in the number of ties needing replacement each year.

3. The number of ties needing annual replacement is most affected by an increase in tonnage.

Surface Life:

1. Degree of curvature has a limited effect on the surfacing cycle.

2. The track geometry rating has the greatest effect on the surfacing cycle.

3. An increase in the input variables (with the exception of track modulus) causes a decrease in the surfacing cycle.

8. RECOMMENDATIONS FOR FURTHER WORK ON THE TRACK SYSTEM MODEL

1. At present, the TSM has only been calibrated to two sets of data. Although the results given are reliable, more detailed calibration to different types of track/traffic conditions is required.

2. The above work requires that field data be collected and supplied by the railways -- at times a most difficult task. Railways have only recently begun to collect some of these data necessary for prediction of track deterioration. They are still far from having all the required data, or even from having the processes required to collect some of the data. The only way to obtain these data, or at least to initiate the process for collecting certain data, is to show a need for it. Models such as TSM are ideal for this purpose. Development of the TSM clearly highlighted some of the shortcomings of existing data.

3. TSM is currently in LOTUS 1-2-3 spreadsheet format. The Wheel Force, Tie Life, and Surface Life Models have been converted to FORTRAN coding. The Rail Life Model has yet to be converted.

4. The Rail Life, Tie Life, and Surface Life Models in TSM all use the predicted forces from the Wheel Force Model. The force equations in this model were based on data on 100 ton-hopper cars. These equations were applied to various cars with different loads by converting the imposed loads to the unsprung mass. With proper data for additional car types, the validity of this approach can be investigated further, and if necessary the equations can be revised or updated accordingly. The equations developed and used in the other models may also be upgraded continually as more research findings on the degradation processes of various track components become available.

5. At present, all submodels of TSM operate independently. That is to say, the condition of the rail does not have any effect on the number of ties needing replacement each year. Further work is needed in this area to incorporate the interaction effect of the individual components of the track.

APPENDIX A

SENSITIVITY RUNS ON THE TIE LIFE MODEL

A.1 With Respect to Speed -- Combined Graph

A.2 With Respect to Tonnage -- Combined Graph

A.3 With Respect to Track Geometry -- Combined Graph

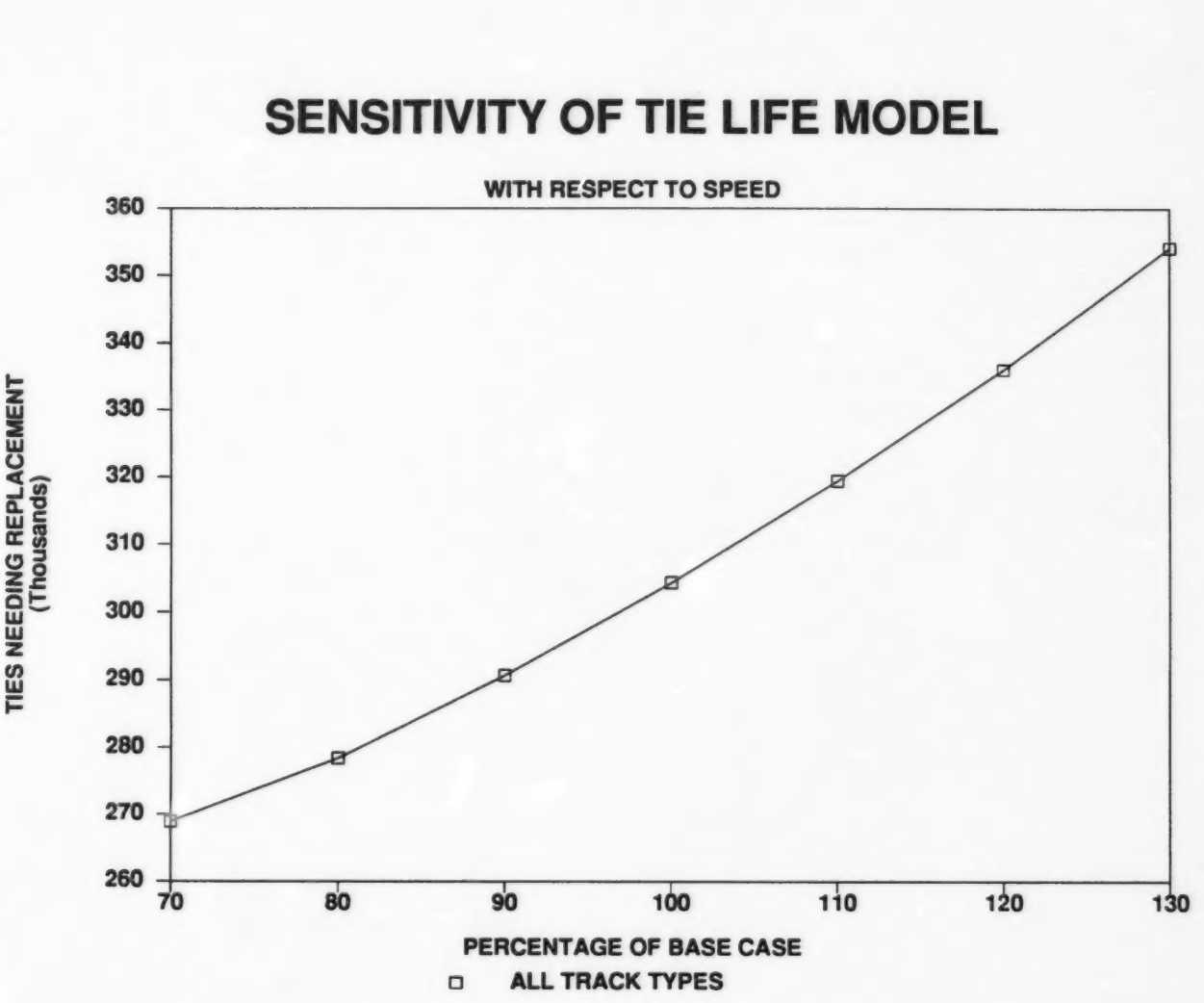
A.4 With Respect to Tonnage -- Effects Separated Into Different Curve Categories

A.5 With Respect to Speed -- Effects Separated Into Separate Curve Categories

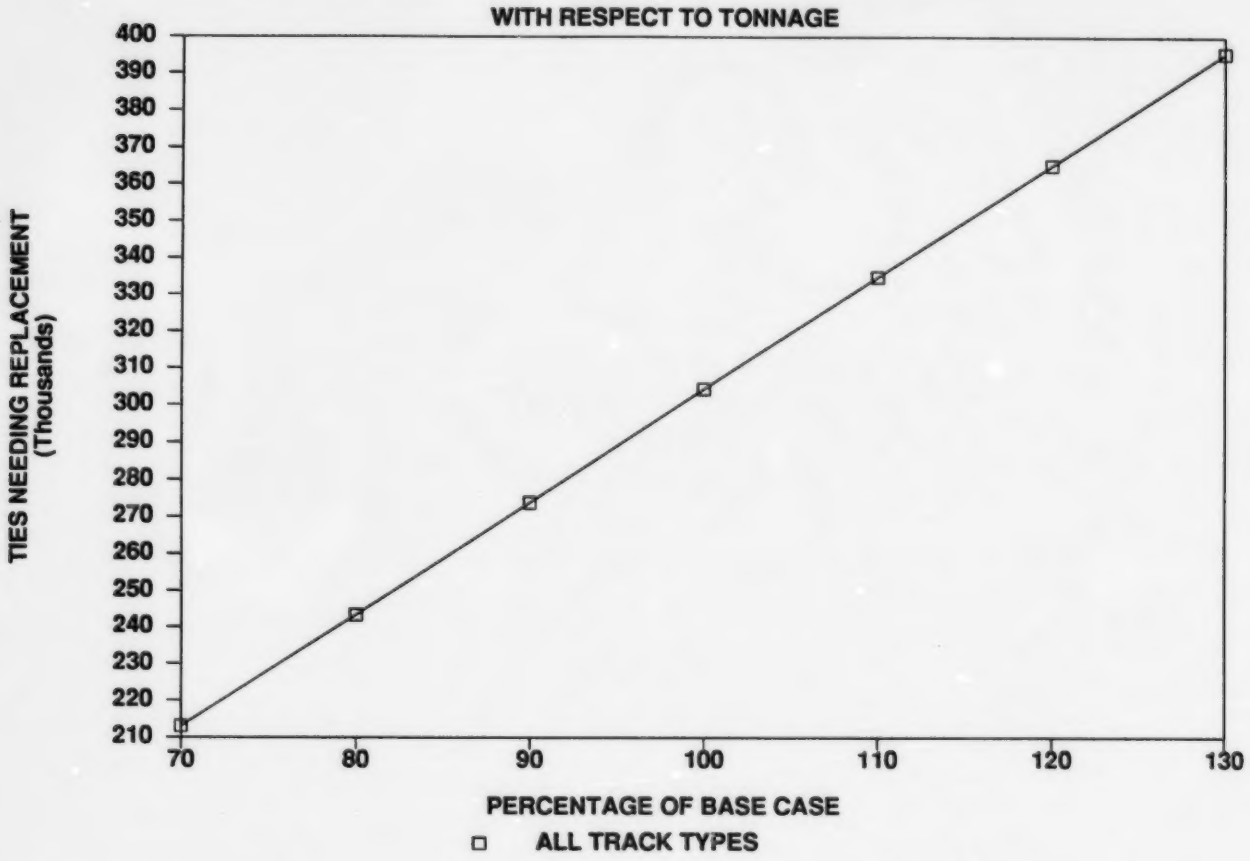
A.6 With Respect to Track Geometry -- Effects Separated Into Separate Curve Categories

A.7 With Respect to Different Equipment

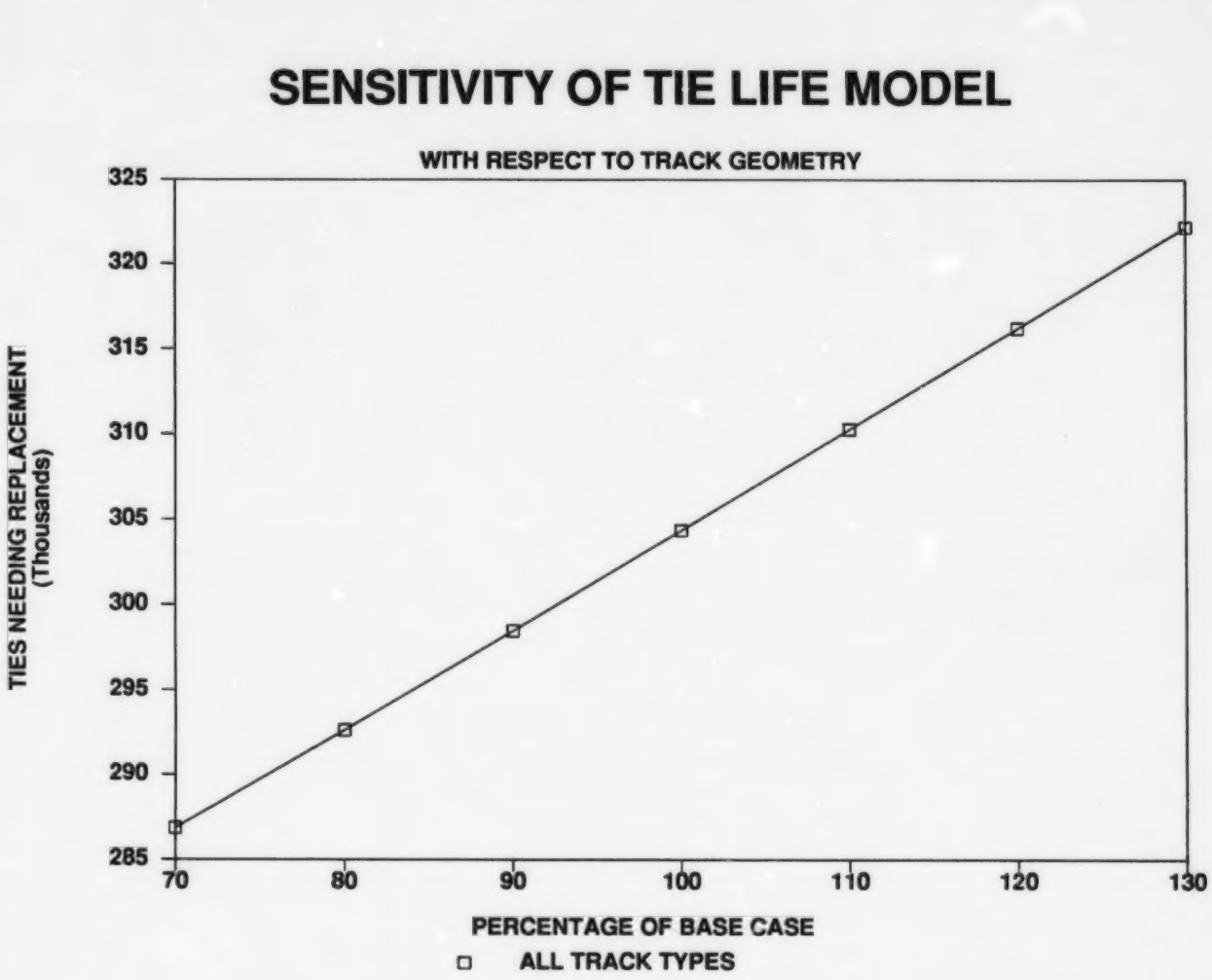
A.8 With Respect to Different Equipment -- Tie Plate Size and Number of Spikes Kept Constant



Graph A.1 With Respect to Speed -- Combined Graph

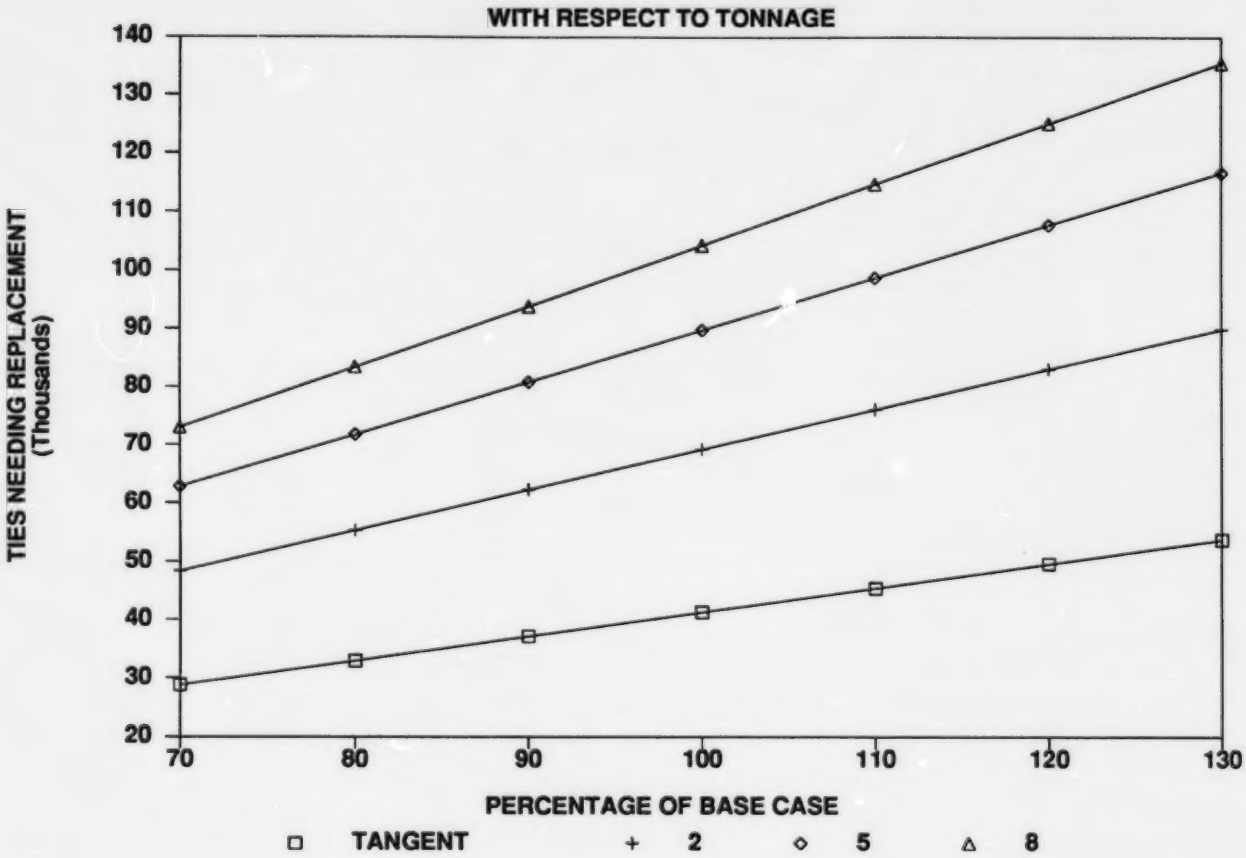


Graph A.2 With Respect to Tonnage -- Combined Graph

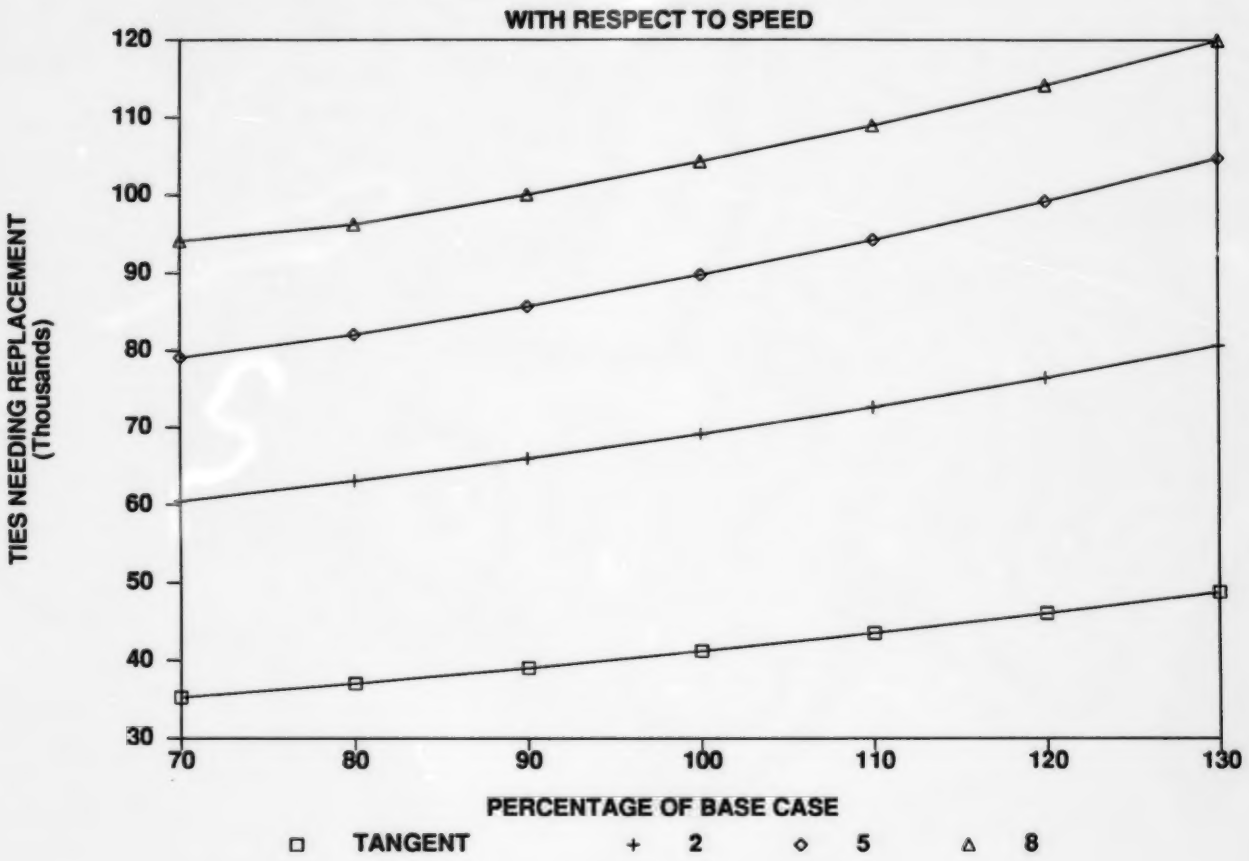


Graph A.3 With Respect to Track Geometry -- Combined Graph

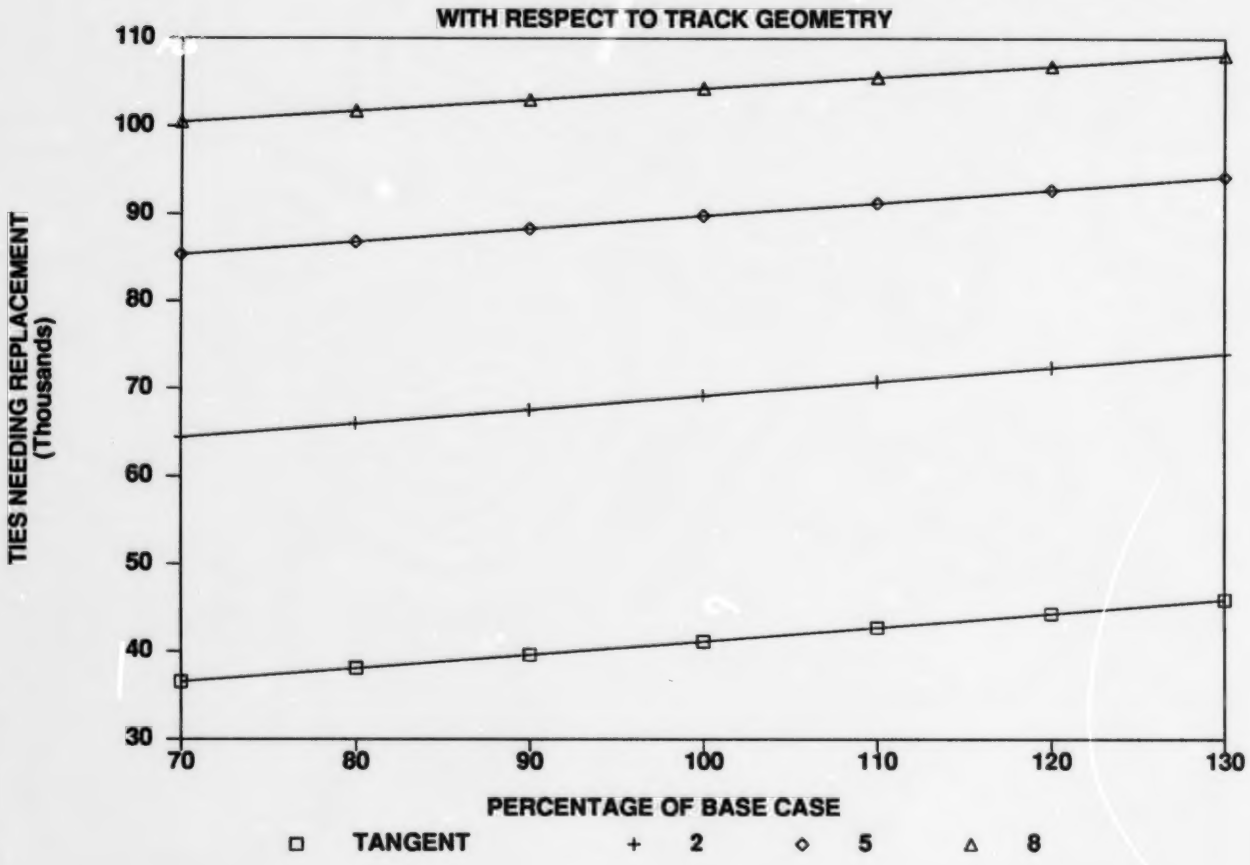
SENSITIVITY OF TIE LIFE MODEL



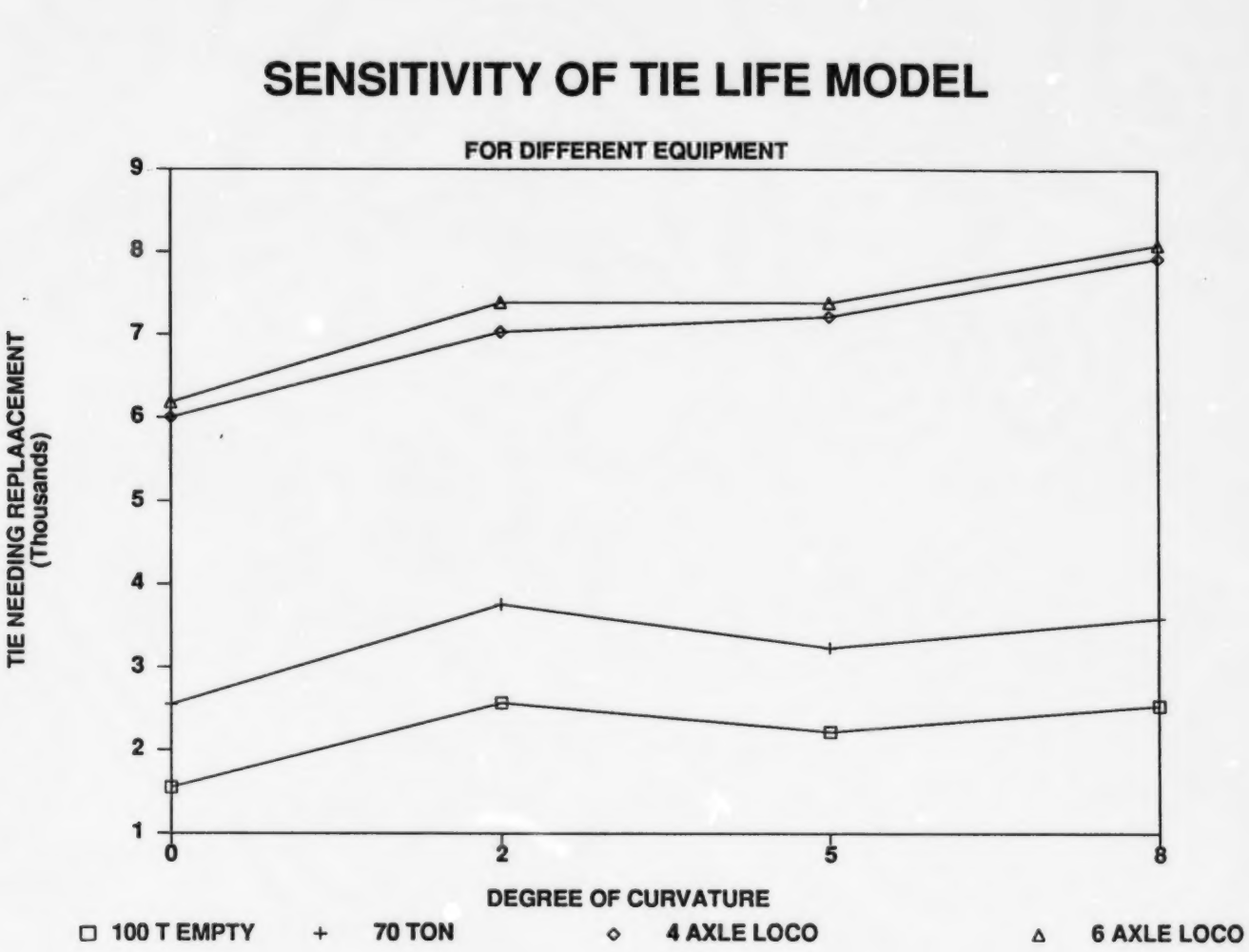
Graph A.4 With Respect to Tonnage -- Effects Separated Into Different Curve Categories



Graph A.5 With Respect to Speed -- Effects Separated Into Separate Curve Categories

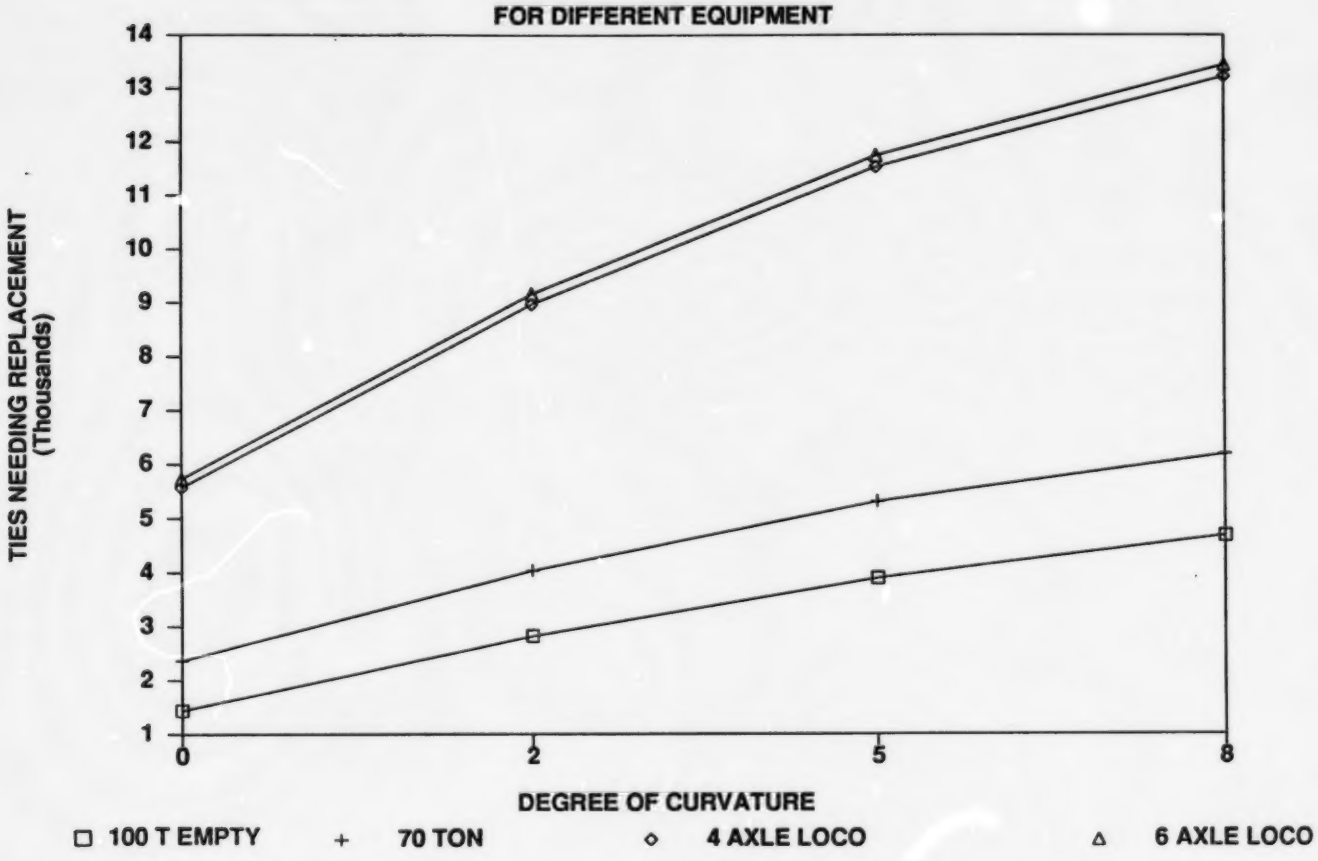


Graph A.6 With Respect to Track Geometry -- Effects Separated Into Separate Curve Categories



Graph A.7 With Respect to Different Equipment

SENSITIVITY OF TIE LIFE MODEL



Graph A.8 With Respect to Different Equipment -- Tie Plate Size and Number of Spikes Kept Constant

APPENDIX B

SENSITIVITY RUNS ON THE SURFACE LIFE MODEL

B.1 With Respect to Tonnage -- Effects Separated Into Different Track Categories

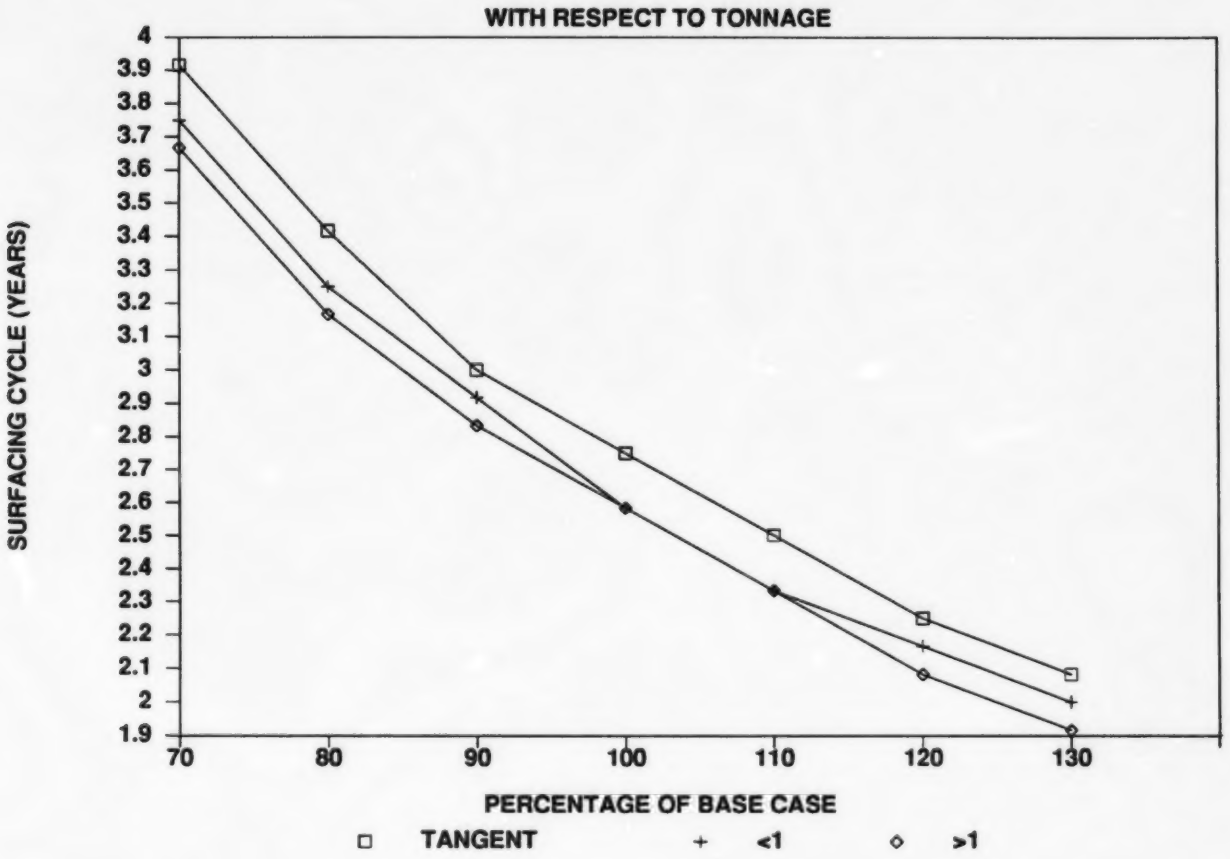
B.2 With Respect to Speed -- Effects Separated Into Different Track Categories

B.3 With Respect to Track Geometry -- Effects Separated Into Different Track Categories

B.4 With Respect to Ballast Abrasion -- Effects Separated Into Different Track Categories

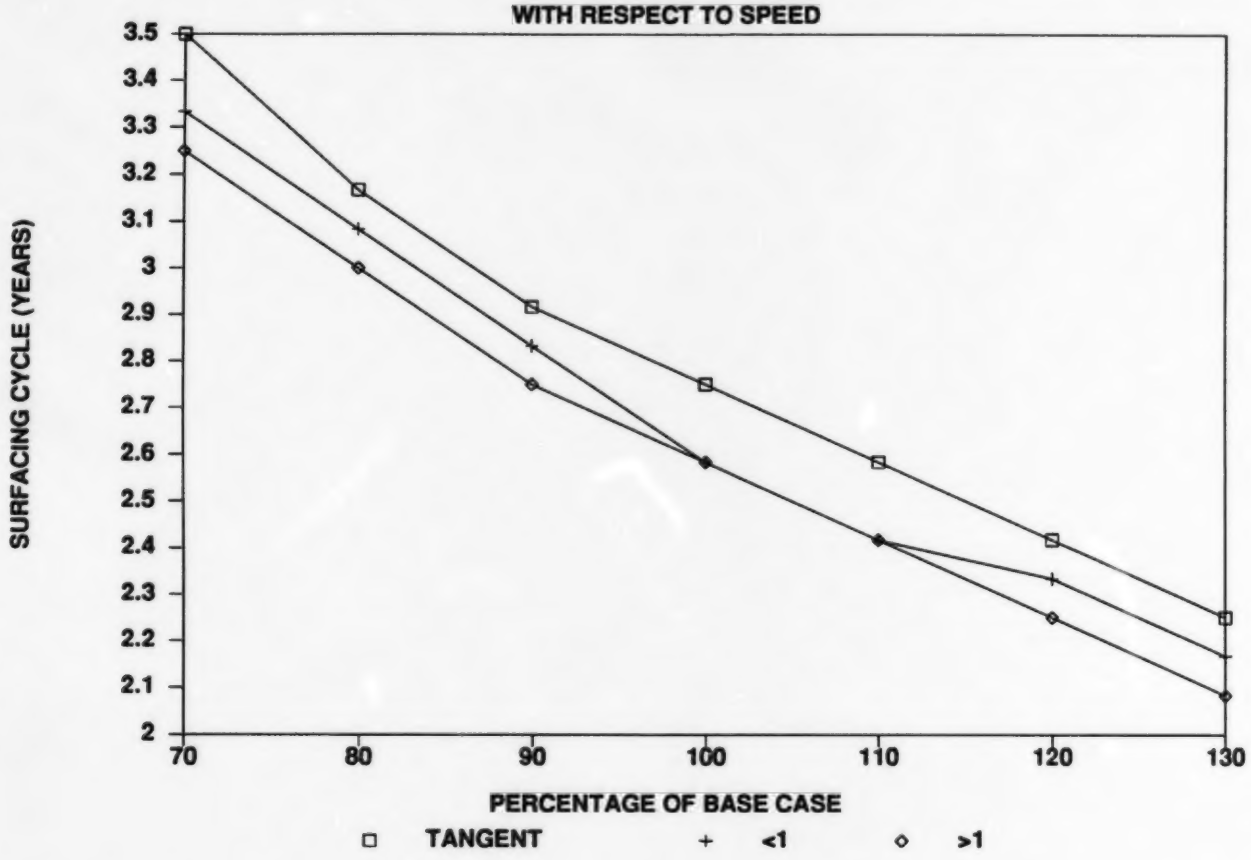
B.5 With Respect to Track Modulus -- Effects Separated Into Different Track Categories

SENSITIVITY OF SURFACE LIFE MODEL



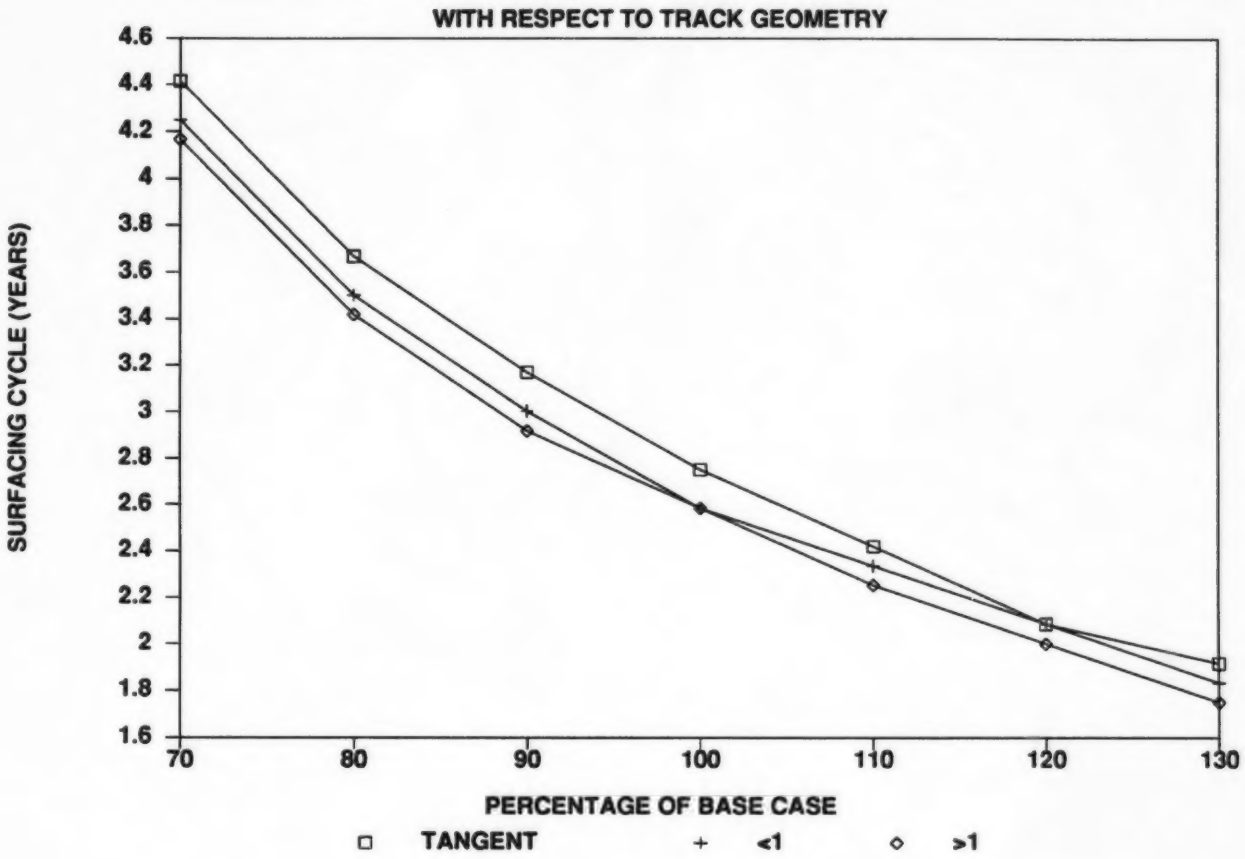
Graph B.1 With Respect to Tonnage -- Effects Separated Into Different Track Categories

SENSITIVITY OF SURFACE LIFE MODEL

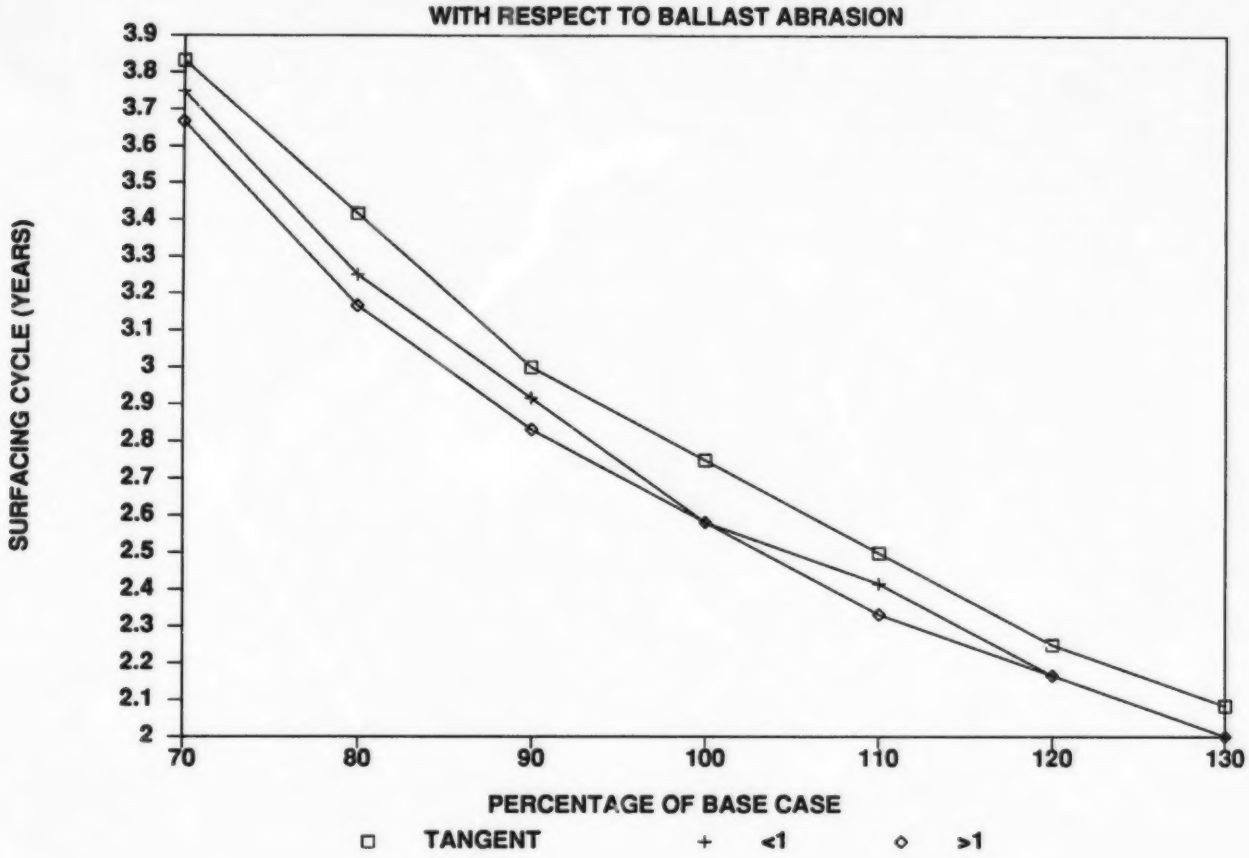


Graph B.2 With Respect to Speed -- Effects Separated Into Different Track Categories

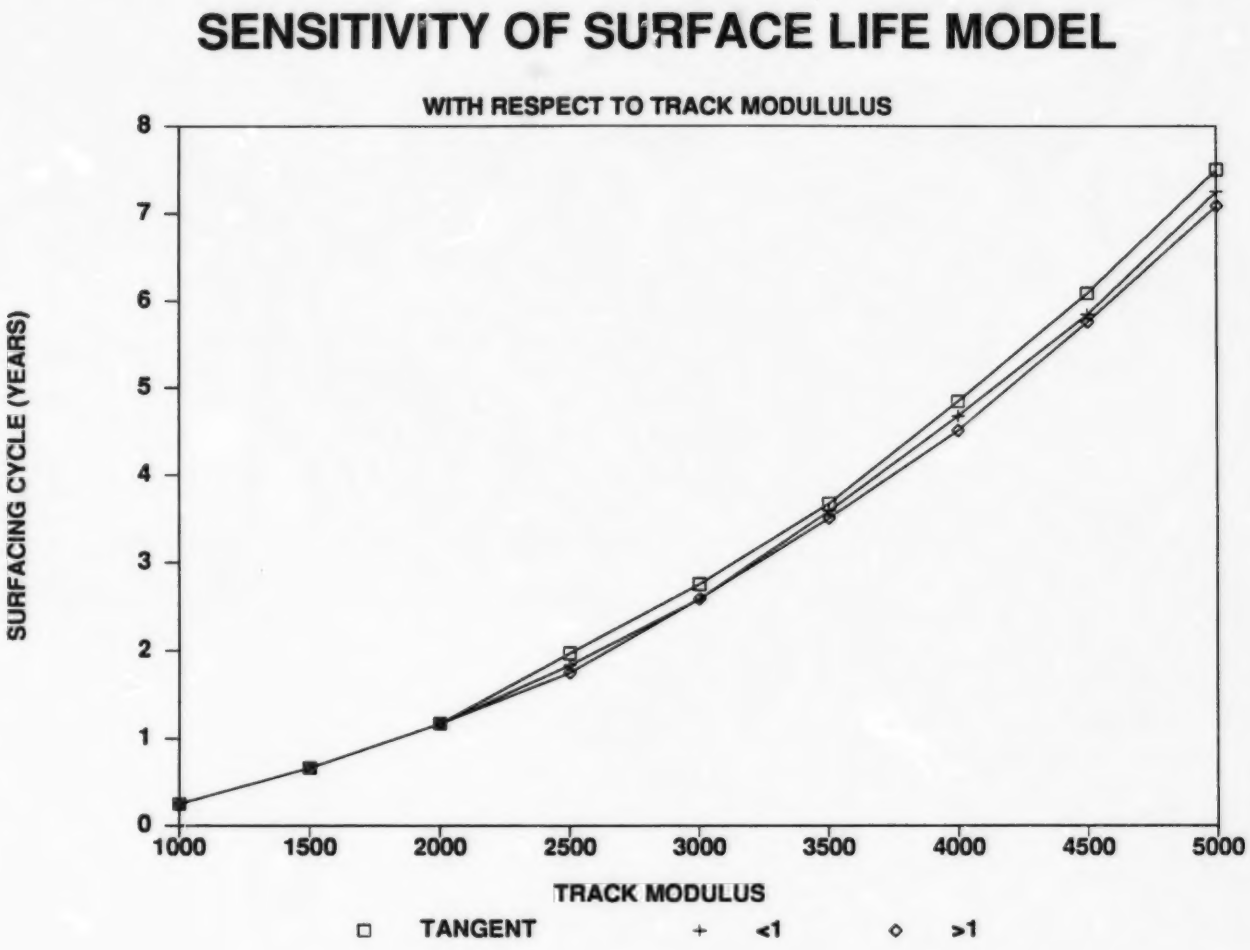
SENSITIVITY OF SURFACE LIFE MODEL



Graph B.3 With Respect to Track Geometry -- Effects Separated Into Different Track Categories



Graph B.4 With Respect to Ballast Abrasion -- Effects Separated Into Different Track Categories



Graph B.5 With Respect to Track Modulus -- Effects Separated Into Different Track Categories

APPENDIX C

SENSITIVITY RUNS ON THE RAIL LIFE MODEL

C.1 With Respect to Tonnage -- Effects Separated Into Different Track Categories

C.2 With Respect to Tonnage on Curved Track -- Effects Shown for Curved Track Only

C.3 With Respect to Tonnage -- Effects Separated Into Different Track Categories

C.4 With Respect to Tonnage -- Effects Shown for Curved Track Only

C.5 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Load and Impact Factors of Sigma.)

C.6 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Load and Impact Factors of 3*Sigma.)

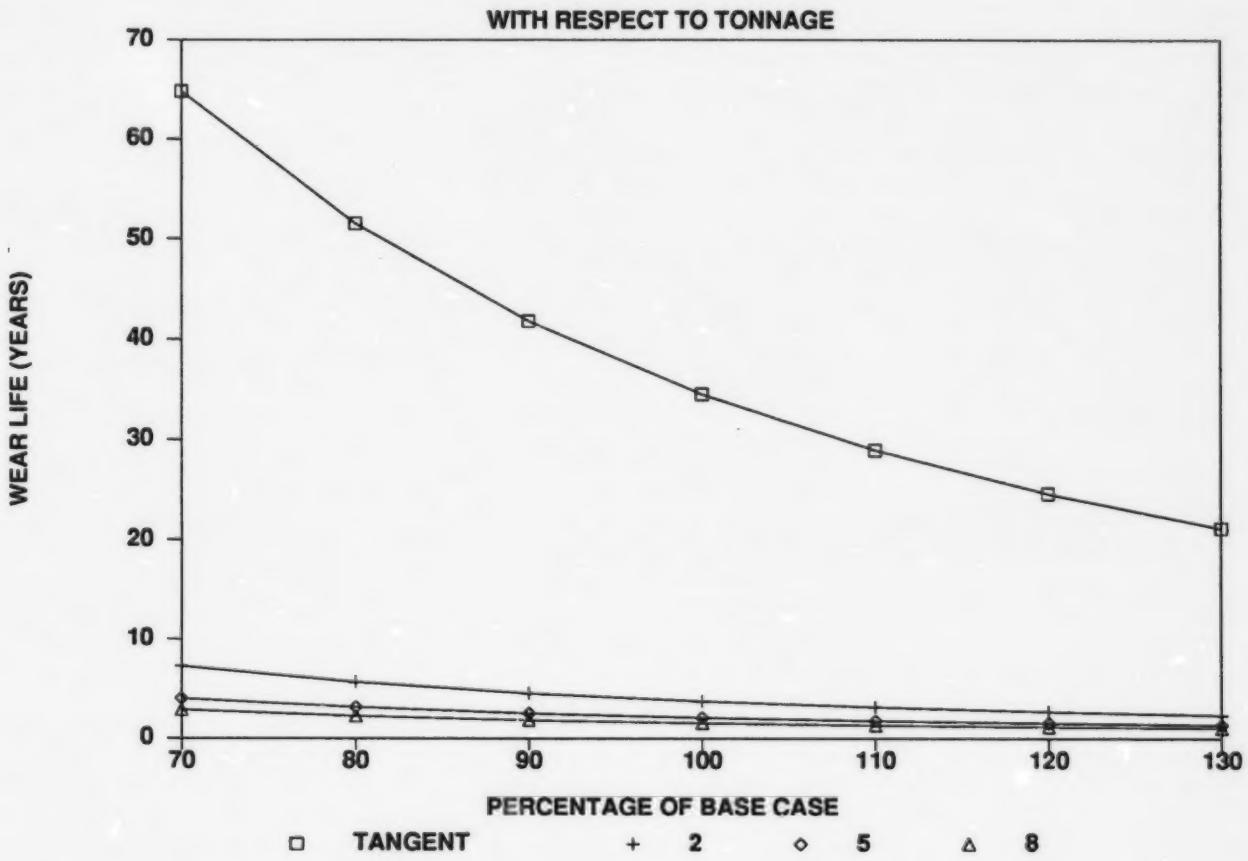
C.7 With Respect to Speed on Curved Track -- Effects Shown for Curved Track Only. (Graphed Using 3*Sigma.)

C.8 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Factors of 3*Sigma.)

C.9 With Respect to Track Geometry -- Effects Separated Into Different Track Categories

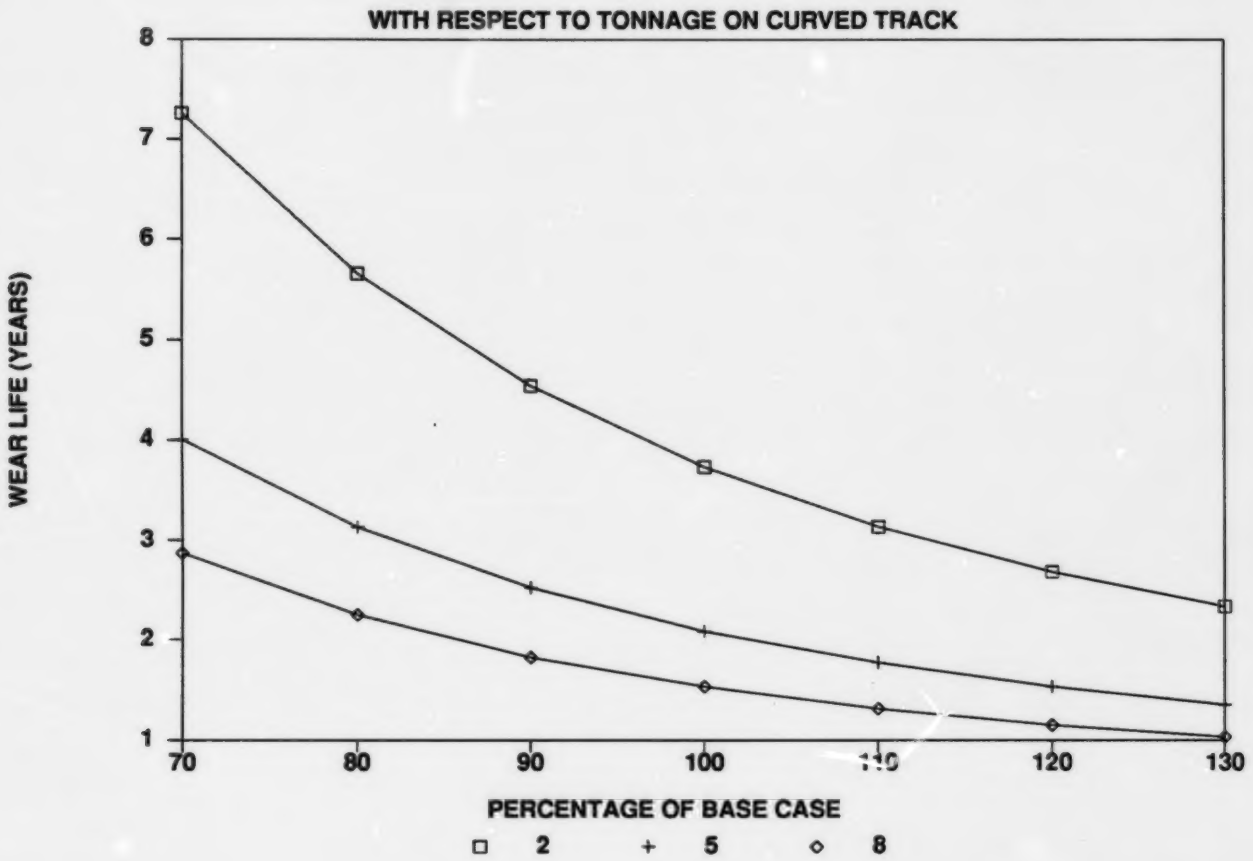
C.10 With Respect to Track Geometry -- Effects Separated Into Different Track Categories

SENSITIVITY OF RAIL LIFE MODEL

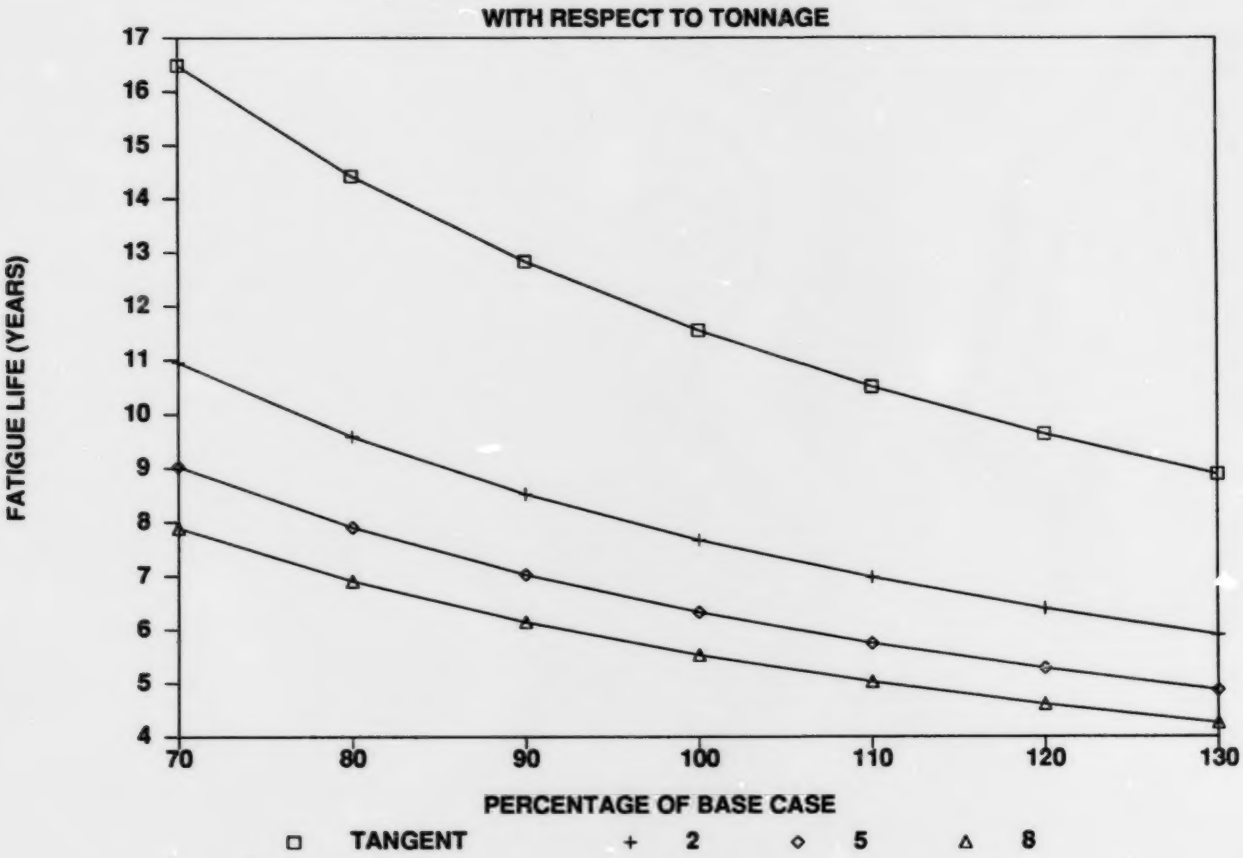


Graph C.1 With Respect to Tonnage -- Effects Separated Into Different Track Categories

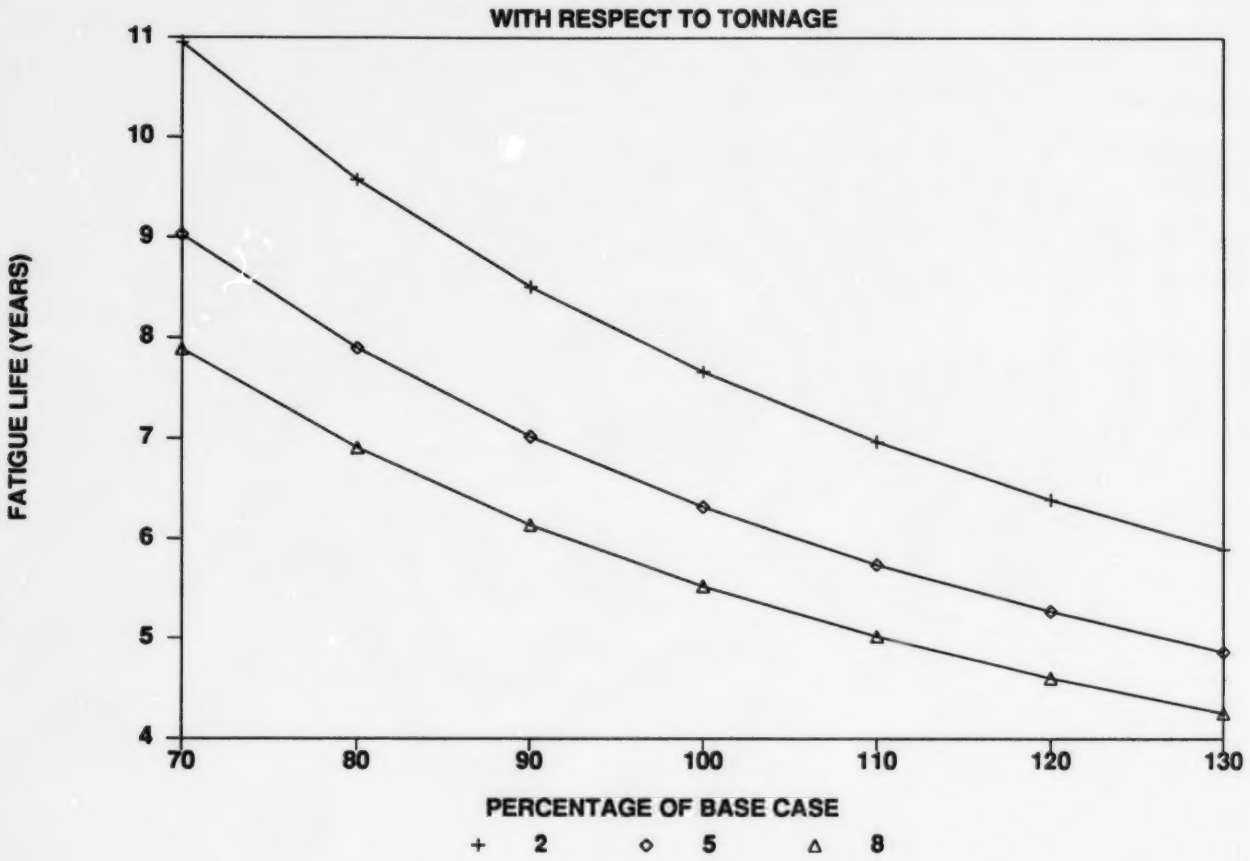
SENSITIVITY OF RAIL LIFE MODEL



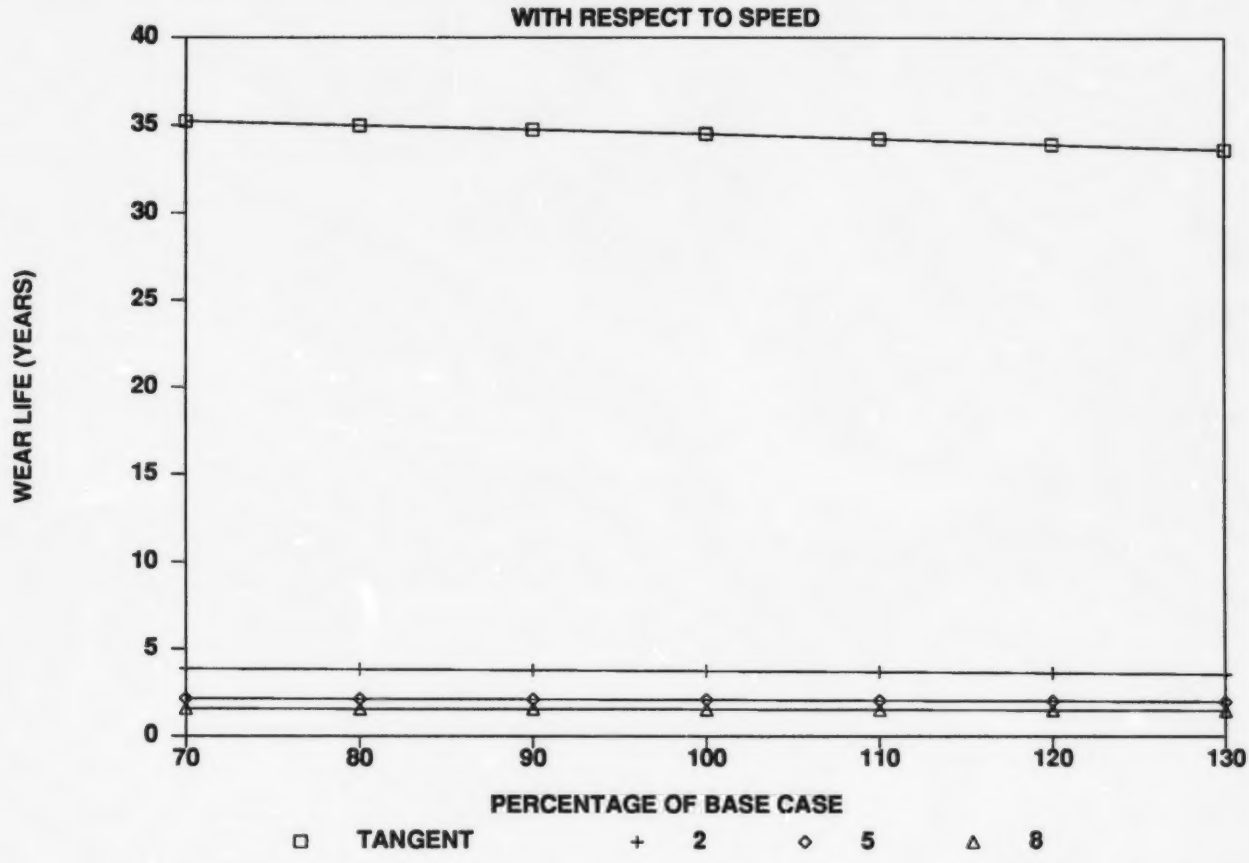
Graph C.2 With Respect to Tonnage on Curved Track -- Effects Shown for Curved Track Only



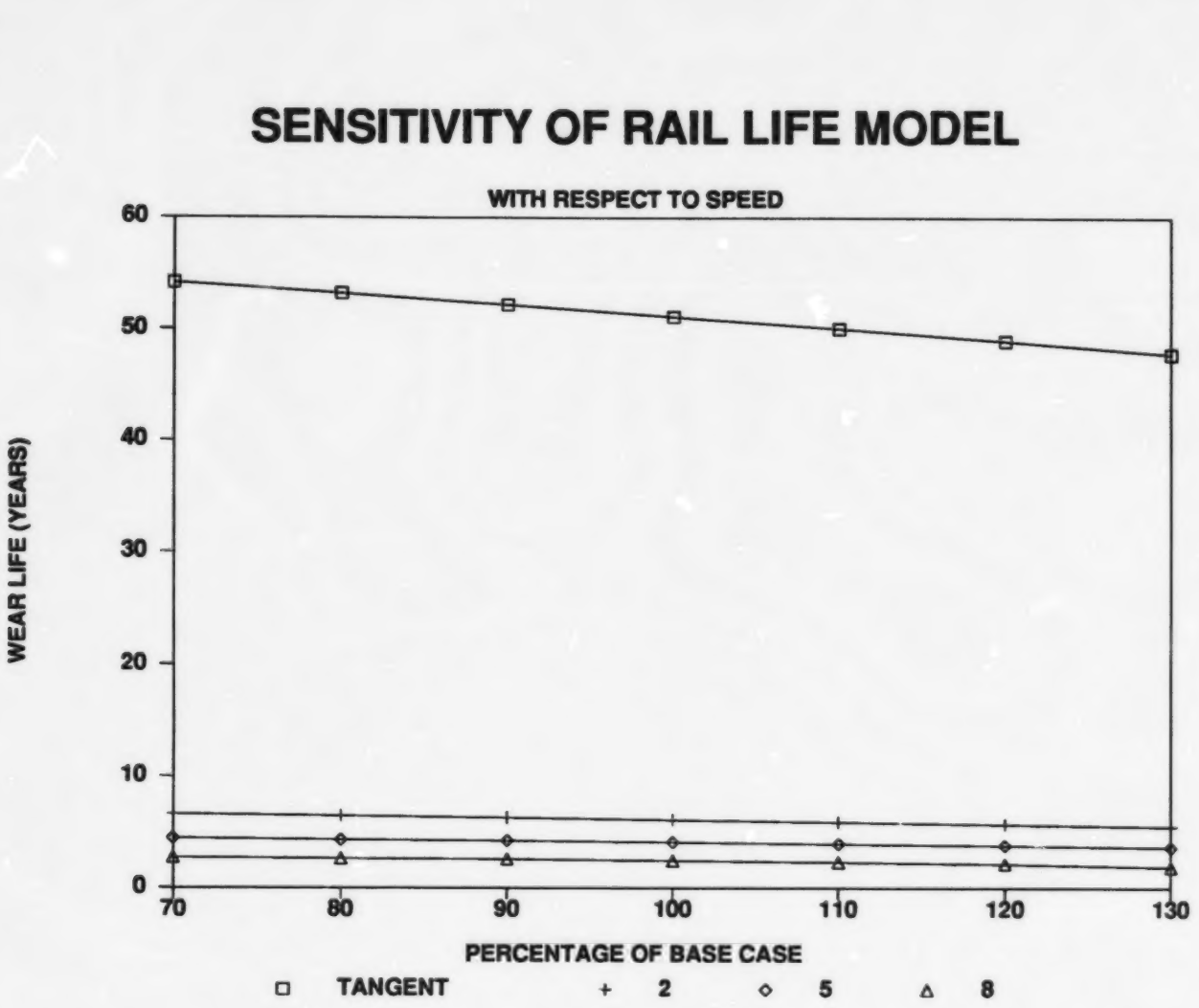
Graph C.3 With Respect to Tonnage -- Effects Separated Into Different Track Categories



Graph C.4 With Respect to Tonnage -- Effects Shown for Curved Track Only

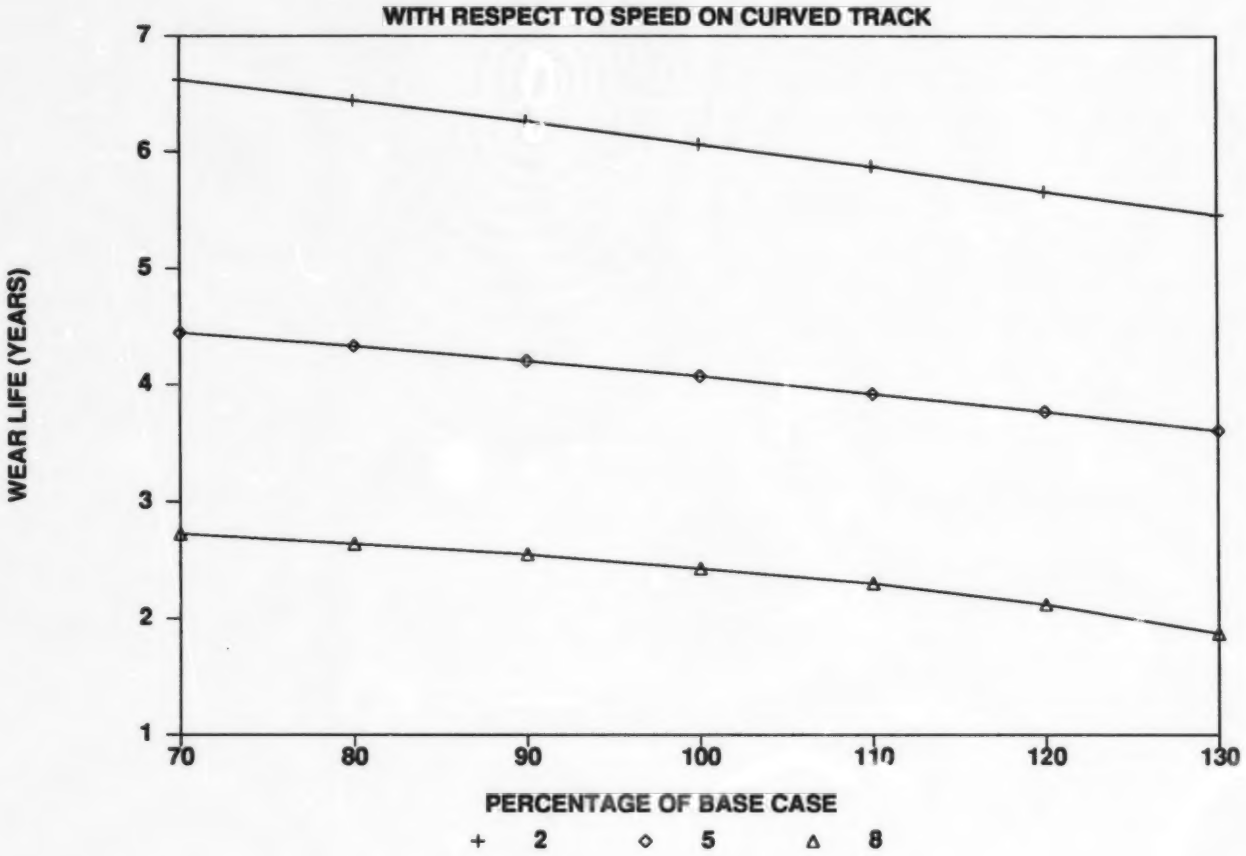


Graph C.5 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Load and Impact Factors of Sigma.)



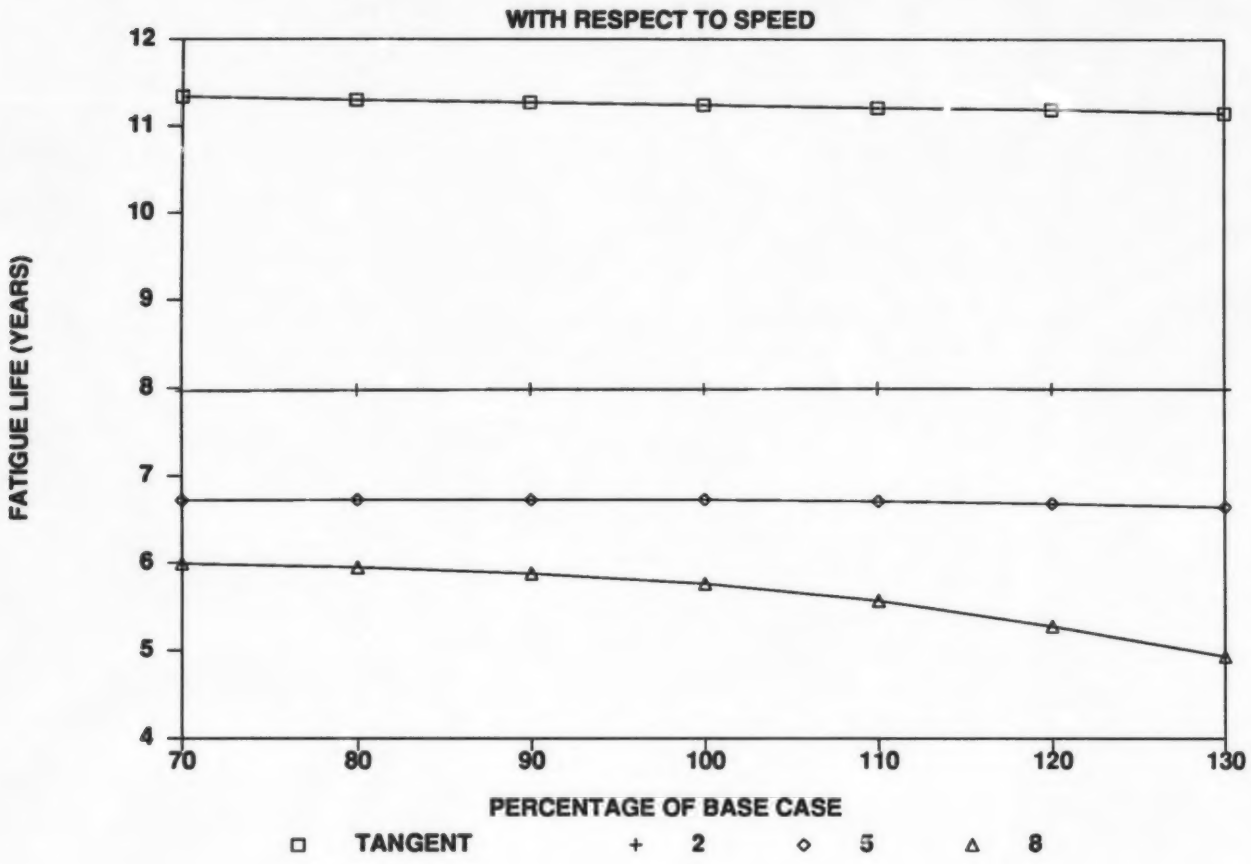
Graph C.6 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Load and Impact Factors of 3*Sigma.)

SENSITIVITY OF RAIL LIFE MODEL



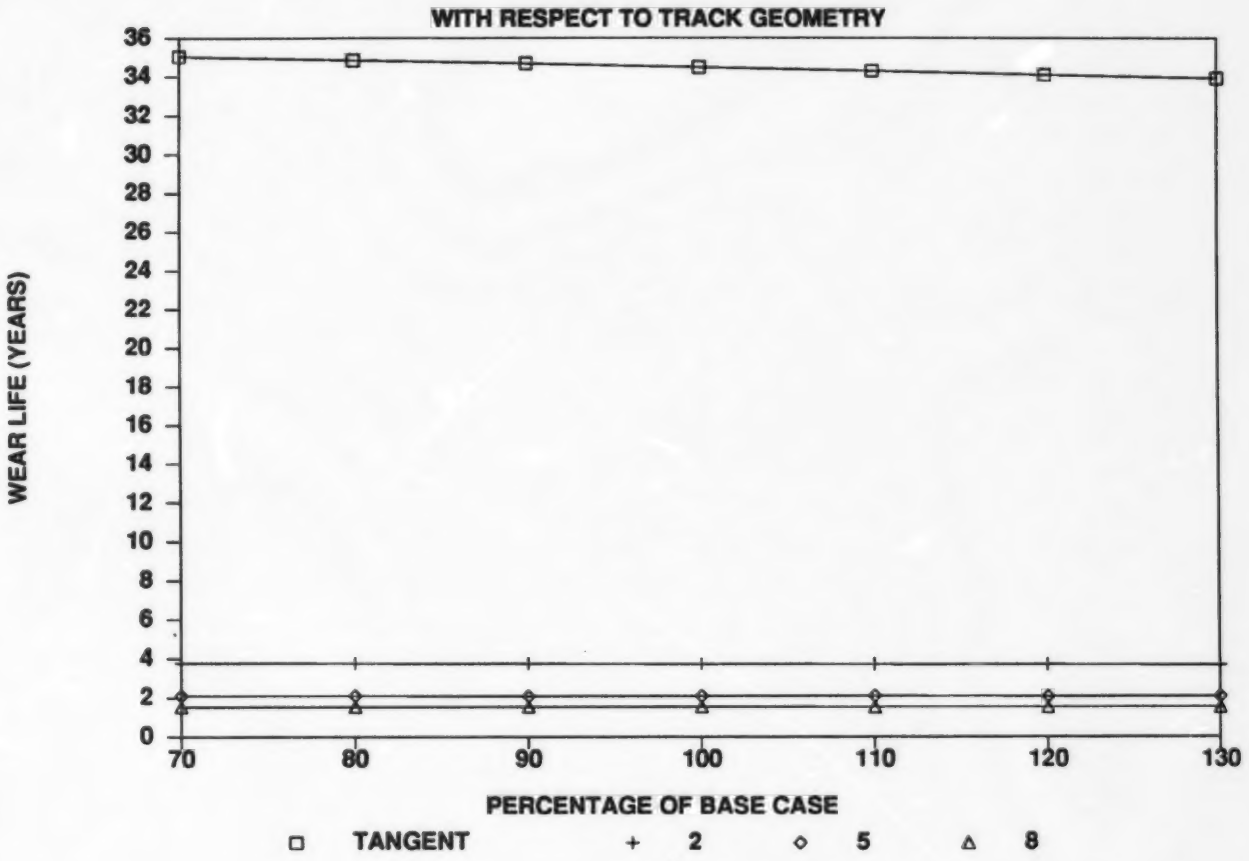
Graph C.7 With Respect to Speed on Curved Track -- Effects Shown for Curved Track Only. (Graphed Using 3*Sigma.)

SENSITIVITY OF RAIL LIFE MODEL

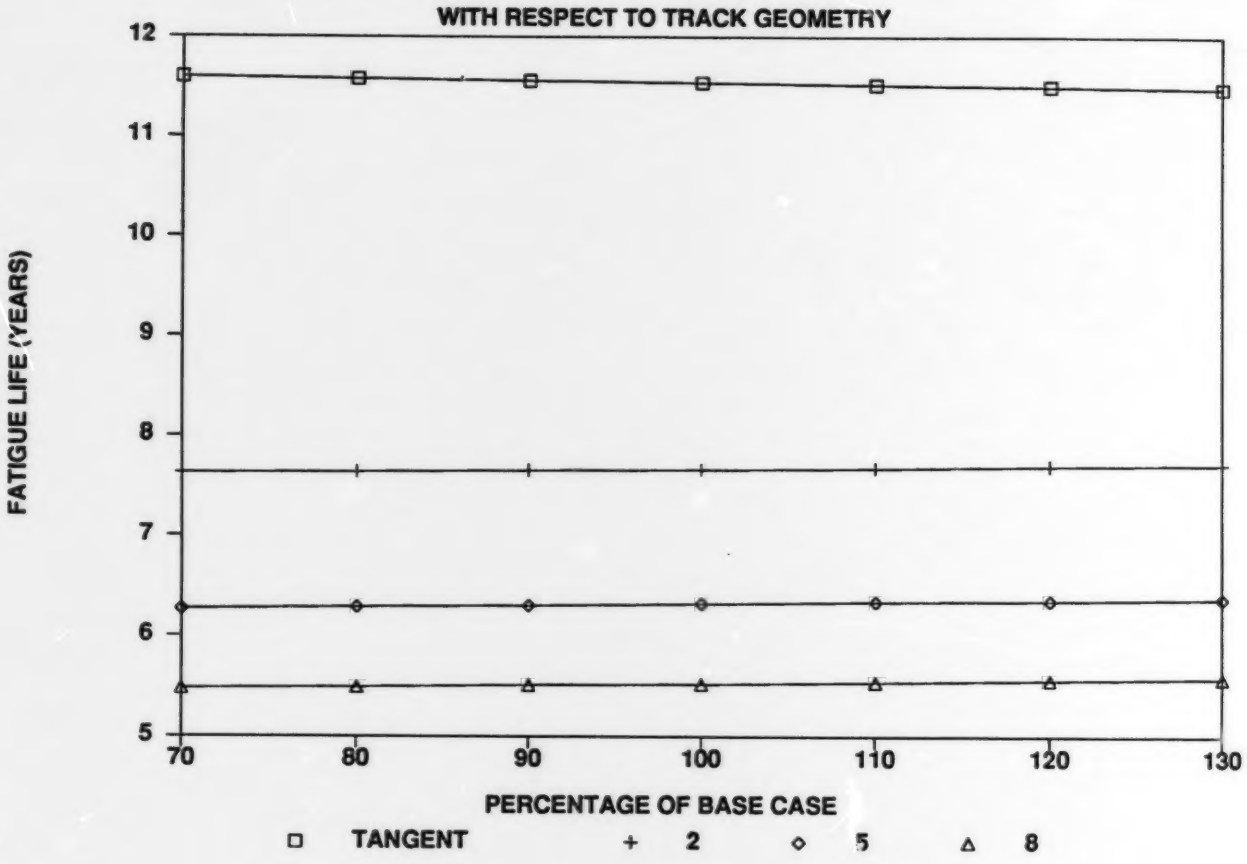


Graph C.8 With Respect to Speed -- Effects Separated Into Different Track Categories. (Graphed Using Factors of 3*Sigma.)

SENSITIVITY OF RAIL LIFE MODEL



Graph C.9 With Respect to Track Geometry -- Effects Separated Into Different Track Categories



Graph C.10 With Respect to Track Geometry -- Effects Separated Into Different Track Categories